THE HEALTH OF OUR AIR

Toward sustainable agriculture in Canada

Canada

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Foreword

It is only in the past four or five decades that scientists have increasingly understood many of the interactions between lands and oceans and the atmosphere—and how human actions may be modifying these exchanges. And it is only in the past two decades that the public and governments have been confronted with clear evidence of the changing composition of the global atmosphere and its likely effects. In the short space of a century, the burning of large quantities of fossil fuels stored in the ground over millions of years has had the largest impact. But the way in which we manage the land and produce food and fiber is by no means negligible. Pollution of the atmosphere affects directly all land creatures and plants, as well as the climate that governs productivity, human activities, and occurrence of extreme events such as drought, floods, and storms.

This book comprehensively addresses those interactions between land and atmosphere that arise because of agricultural practices in Canada. Some of the atmospheric changes may be benign or even beneficial to humans and plants. But there is much evidence to indicate that adverse effects are occurring. These negative effects will continue to increase unless changes occur in how we manage our energy, food, and fiber economies.

The authors wisely point out that the net release of greenhouse gases from agriculture "is usually a symptom of inefficient use of resources." This is also true of other economic sectors contributing to atmospheric changes. It is not just the case for greenhouse gases, but also for problems such as emissions of precursors to low-level ozone and acid rains.

Various means of increasing the efficiency with which we use our resources in agriculture are outlined. Also examined is the significant potential for restoring organic carbon in our soil through conservation tillage and other means, thus reducing atmospheric carbon dioxide. There are many "win–win" opportunities demonstrated, where increased soil and agricultural productivity go hand-in-hand with reducing pollution of the atmosphere. This book provides much of the scientific information needed to develop an effective strategy for Canada's agricultural sector.

Let us hope that this cooperative way of approaching the problems confronting agriculture and the global atmosphere becomes an inspiration for other sectors. As in agriculture, there are many cost-effective "win-win" opportunities for achieving energy efficiency to be found in transportation and forestry that can improve Canada's economic situation and simultaneously help protect the life-giving atmosphere of our small planet.

James P. Bruce, O.C., FRSC
Canadian Climate Program Board

Preface

This book has its roots in two international reports:

- the World Commission on Environment and Development, *Our Common Future*, better known as the "Brundtland" report

- the 1990 report of the Intergovernmental Panel on Climate Change, IPCC.

In 1987, *Our Common Future* brought world attention to problems such as global warming, ozone depletion, desertification, reduced biodiversity, burgeoning demands of a growing population, and the need for a global agenda for change that would make development sustainable. In short, the Commission sought ways to meet present needs without compromising the ability of future generations to meet theirs.

The IPCC, set up by the World Meteorological Organization and the United Nations Environment Program, produced its first scientific assessment in 1990. Several hundred scientists from 25 countries helped prepare and review the scientific data. The IPCC concluded that emissions from human activities are increasing the concentration of greenhouse gases. It warned that this could lead to a warming of the Earth's surface.

These two reports brought climate change to the forefront of the world environmental agenda. In 1992 nations met in Rio de Janeiro to sign the Climate Change Convention, an agreement to reduce greenhouse gas emissions. The IPCC released a second scientific assessment in 1995 stating that "the balance of evidence suggests a discernible human influence on global climate." A further international agreement, signed by 174 countries in Kyoto, Japan, in 1997, agreed to set specific targets for greenhouse gas emissions.

Scientists in Canada, as in other countries, now focused more attention on issues associated with atmospheric pollution, greenhouse gases, and climate. Within the Canadian federal government, the Atmospheric Environment Service (Environment Canada) and programs such as the Green Plan provided further support. Indeed, the four federal, science-based, natural resources departments of Environment, Fisheries and Oceans, Natural Resources, and Agriculture and Agri-Food joined forces and signed a Memorandum of Understanding for Science and Technology for Sustainable Development in 1995. The goal was to enhance cooperative research in areas of mutual concern such as climate change.

The Research Branch of Agriculture and Agri-Food Canada initiated a research program in greenhouse gases and ground-level ozone in 1992 in support of sustainable development. The program involved scientists working for the federal government, universities, provincial agencies, and the private sector. After 6 years, we now report our findings to the Canadian public.

The Health of Our Air joins *The Health of Our Soils* and the forthcoming *The*

Health of Our Water as a series of
scientific assessments evaluating the
natural resources upon which
Canadian agriculture depends.

This book contains our most recent
research findings. As the research
continues, better estimates of
greenhouse gas emissions will emerge.
New, more efficient technologies will
be developed, and we will learn more
about the relationship between
agriculture and the health of air. The
Research Branch of Agriculture and
Agri-Food Canada is committed to

research in support of sustainable
development of the Canadian
agriculture sector.

J.B. Morrissey
Assistant Deputy Minister
Research Branch
Agriculture and Agri-Food Canada

R. Slater
Senior Assistant Deputy Minister
Environment Canada

1. Introduction

Agriculture is tied tightly to the environment. Future food production depends on preserving soil, air, and water quality; in turn, the way we farm influences these resources. As a result, we need to assess, from time to time, the changes taking place in the environment, both to ensure that farming can be sustained and to measure its effect on other ecosystems. An earlier report considered *The Health of Our Soils*; in this companion, we focus on *The Health of Our Air*.

Unlike soil, which is fixed in place, air moves and mixes freely around the globe. Air at the earth's surface can exchange with air many kilometres up within hours, and air currents can move around the world in a matter of days. Some of the carbon dioxide released by fires in Asia may be absorbed by orchards in Ontario, and some of that released from decomposing straw in Saskatchewan is taken up by the jungles of South America. As a result, we have to view the health of our air from a global perspective.

Importance of atmospheric health

Our atmosphere has many essential functions. It is a reservoir of gases upon which life depends: carbon dioxide and nitrogen for plant growth, oxygen for us to breathe, water vapor for rain that refreshes the land. It insulates the planet against temperature extremes and filters out harmful radiation from the sun. It even helps detoxify harmful substances released into it, either hastening their breakdown or diluting and dispersing them. Because living things depend so completely and in so many ways on the atmosphere, any change in its makeup should concern us.

Our changing atmosphere

The air is always being recycled by exchange of gases and particles with land, water, and living things. The rates of gases entering the atmosphere are usually balanced by rates of gases lost, so that the composition of the atmosphere has remained nearly constant for many centuries. This balance has been disrupted, however, by increasing emissions from human activity, so that some gases are now accumulating, altering the composition of the air.

One of the most noticeable changes, in recent years, has been an increase in concentrations of some "greenhouse gases": carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). These gases absorb some of the energy radiating from the earth, thereby warming the atmosphere. A build-up of greenhouse gases, therefore, is expected to increase global temperature over time.

Greenhouse gases are not the only constituents of air whose concentration is changing. The levels of other constituents such as nitrogen and sulfur gases, ozone (O_3), gaseous organic compounds, and suspended particles are also increasing as a result of human activity, including

agriculture. These changes, like those in greenhouse gases, may affect climate and the health of the environment.

Growing concern over the changing atmosphere has prompted global efforts to reduce emissions. These include recent international agreements to limit emissions of O_3-depleting chemicals (Montreal Protocol) and a Canada–US agreement on air-pollution. Perhaps most noteworthy is a treaty signed in Kyoto, Japan in December 1997 where 174 countries, including Canada, agreed to curb emissions of greenhouse gases.

Objectives of this report

Agriculture occupies a larger portion of global land area (about 35%) than any other human activity. Because of its scale and intensity, agriculture emits a lot of gases into the atmosphere. For example, agriculture is a main source of greenhouse gases, accounting for about 25% of the CO_2, 50% of the CH_4, and 70% of the N_2O released via human activity globally. As well, agriculture accounts for more than 50% of ammonia released into the air.

But because farmlands are managed so intensively, farmers can control, at least partly, the amounts of gases released. Various ways of farming produce different emissions; and by choosing new practices, it may be possible to reduce emissions. For some gases, farmlands may, in fact, even be made to absorb more than they emit, thereby helping to restore air quality.

In this report, we focus on the effect of Canadian agriculture on the atmosphere. Specifically, we try to answer three questions:

- How do farming practices affect the composition of the atmosphere?

- What is the amount of agriculture's emissions to the air?

- How can we reduce these emissions?

Scope of this report

The most pronounced change in the atmosphere, and the one with greatest potential consequence, is the build-up of greenhouse gases. Hence, this report addresses in detail the amounts of greenhouse gas emission and possible ways of reducing them. We limit our discussions mainly to agricultural production itself and, except for ethanol, do not consider the fate of agricultural products once they leave the farm. Many of the findings presented were obtained from a national research program initiated by Agriculture and Agri-Food Canada in 1992.

Besides focusing on greenhouse gases, we also consider several other current atmospheric issues, though in less detail: ground-level O_3, ammonia, ultraviolet (UV) radiation from the sun, aerosols, nitrogen oxides, pesticides, and farm-related odors. Wherever possible, our discussion is based on findings from Canadian studies but, where Canadian results are only just emerging, we have drawn on results from elsewhere.

Changes to the global environment may have pronounced effects on Canadian agriculture in the future: changing concentrations of CO_2 may affect plant growth; increasing temperature may allow greater diversity of crops but favor crop pests; changing patterns of precipitation may favor some areas but induce drought in others. Such changes remain hard to predict. Because of this uncertainty and the constraints of space in this report, how agriculture will adapt to future changes is only referred to indirectly; we await results of ongoing research to clarify this issue further.

Reading this report

This report is written for students of environmental issues, farmers, agricultural professionals, decision-makers, and others who want to understand the links between agriculture and air quality. The reader does not need a scientific background to read the report, though a rudimentary knowledge of chemical notation will be helpful. For example, we refer to various compounds containing nitrogen (N), carbon (C), oxygen (O), and hydrogen (H), elements that are the main constituents of greenhouse gases and organic matter. For the inquisitive reader, we have listed some important compounds in the box on this page.

The information presented is gleaned from numerous sources, both Canadian and international. To allow for easier reading, we have not quoted individual sources but have provided a general bibliography at the end. More detailed information as well as some of the original sources may be found there.

Principal atmospheric constituents		
Elements and compounds	Symbol	Atomic or molecular weight
Elements		
Hydrogen	H	1
Carbon	C	12
Nitrogen	N	14
Oxygen	O	16
Gases		
Methane[1]	CH_4	16
Ammonia	NH_3	17
Nitrogen	N_2	28
Nitric oxide	NO	30
Oxygen	O_2	32
Carbon dioxide[2]	CO_2	44
Nitrous oxide[3]	N_2O	44
Nitrogen dioxide	NO_2	46
Ozone	O_3	48

[1] 1 g of CH_4 contains 0.75 g of C.
[2] 1 g of CO_2 contains 0.27 g of C.
[3] 1 g of N_2O contains 0.64 g of N.

2. Canadian agriculture and greenhouse gases

Canadian agriculture is diverse, with a variety of crops and livestock in a range of climates and soils. Emissions of greenhouse gases are also highly variable, changing with type of farming operation and even within individual farms. To estimate the emission of greenhouse gases from Canadian farms, therefore, we have to first consider briefly the nature of farming in Canada.

A glance at Canadian agriculture

The Canadian landmass has been classified into 15 ecological zones (ecozones) based on soil and climate. Most of Canada's land is forested, and only about 5% is suitable for farming, mainly in two ecozones—the Prairies and the Mixed Wood Plains of the St. Lawrence River (Fig. 1). The Prairies alone account for about 80% of Canada's 68 million hectares of farmland. Two-thirds of all farmland is used for crops and "improved" pastures (those that are seeded,
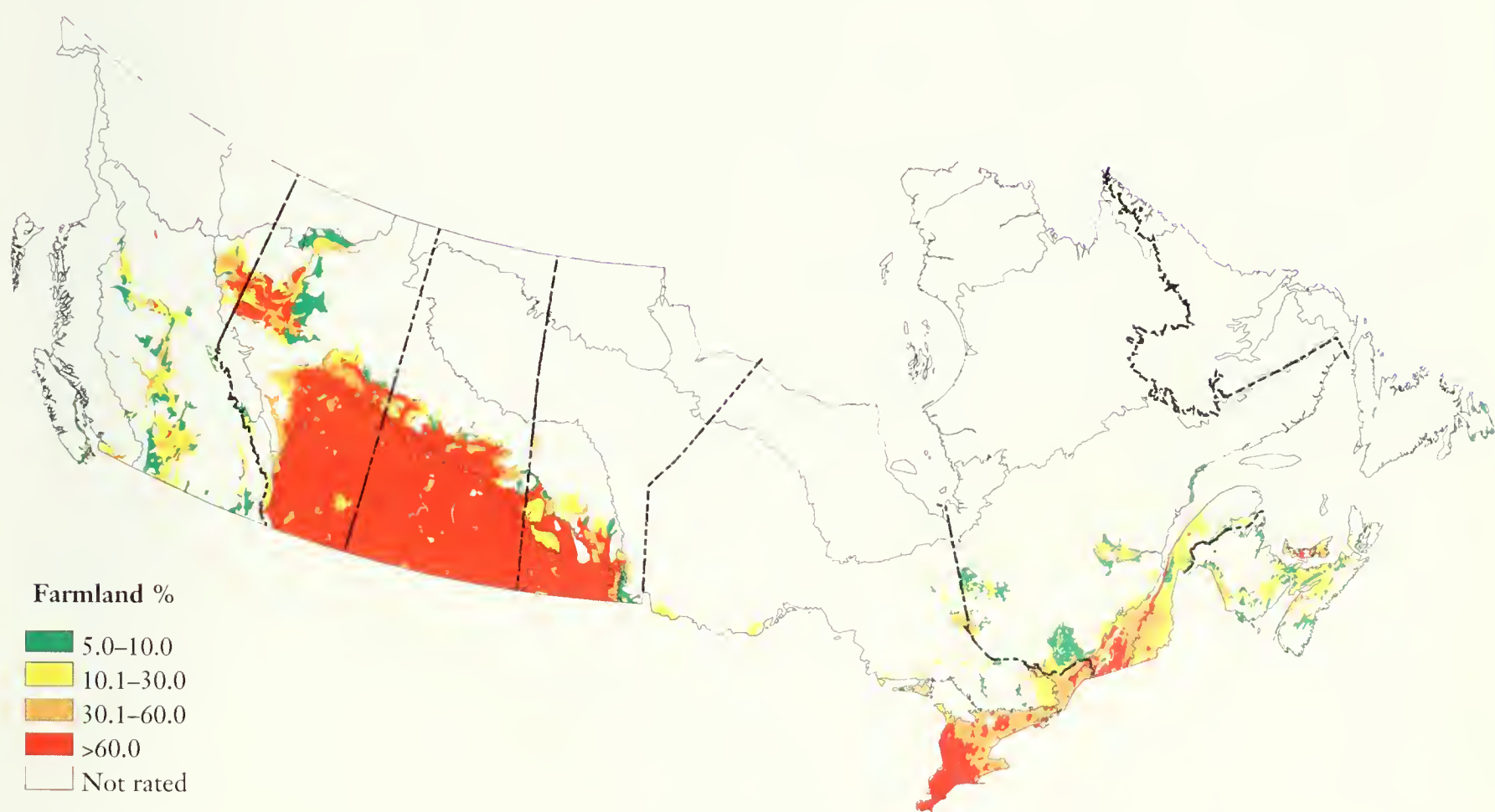
Farmland %

- 5.0–10.0
- 10.1–30.0
- 30.1–60.0
- >60.0
- Not rated

Figure 1

Farmland as a proportion of land area in various parts of Canada in 1996. (F. Wang and D.B. Gleig, AAFC)

drained, fertilized, or weeded); the rest is occupied by "unimproved" pastures (largely native grasslands), buildings, barnyards, bush, sloughs, and marshes. The various types of pasture together account for about 30% of farmland (Fig. 2).

The relative areas devoted to annual crops and animal husbandry vary widely across the country. For example, large areas of the Prairies are used almost exclusively for cropland (Fig. 3), whereas small pockets of concentrated livestock production exist in areas of British Columbia and the southern regions of Alberta, Ontario, and Quebec (Fig. 4).

Although all ecosystems share common nutrient pathways, agriculture has unique features when compared to other land uses such as forestry. Farmlands, particularly those devoted to annual crops, are intensively managed. Moreover, the time cycle for agricultural crops is short, often annual. As a result, agriculture can respond quickly to climatic, economic, and policy events by changing land use and cropping systems, and there can be large shifts in just a few years (Table 1). Finally, agricultural ecosystems are quite "open," involving continual transfer of material in (e.g., fuel, fertilizers, and pesticides) and material out (e.g., crop yields and animal products). Unlike forests, which gradually increase their store of wood, farmlands rarely accumulate vegetation over the long term. Because of these unique features, studying and estimating greenhouse gas emissions from farms differs from that in other ecosystems.

Pasture %

- ≤5.0
- 5.1–15.0
- 15.1–40.0
- 40.1–60.0
- >60.0
- Excluded from analysis
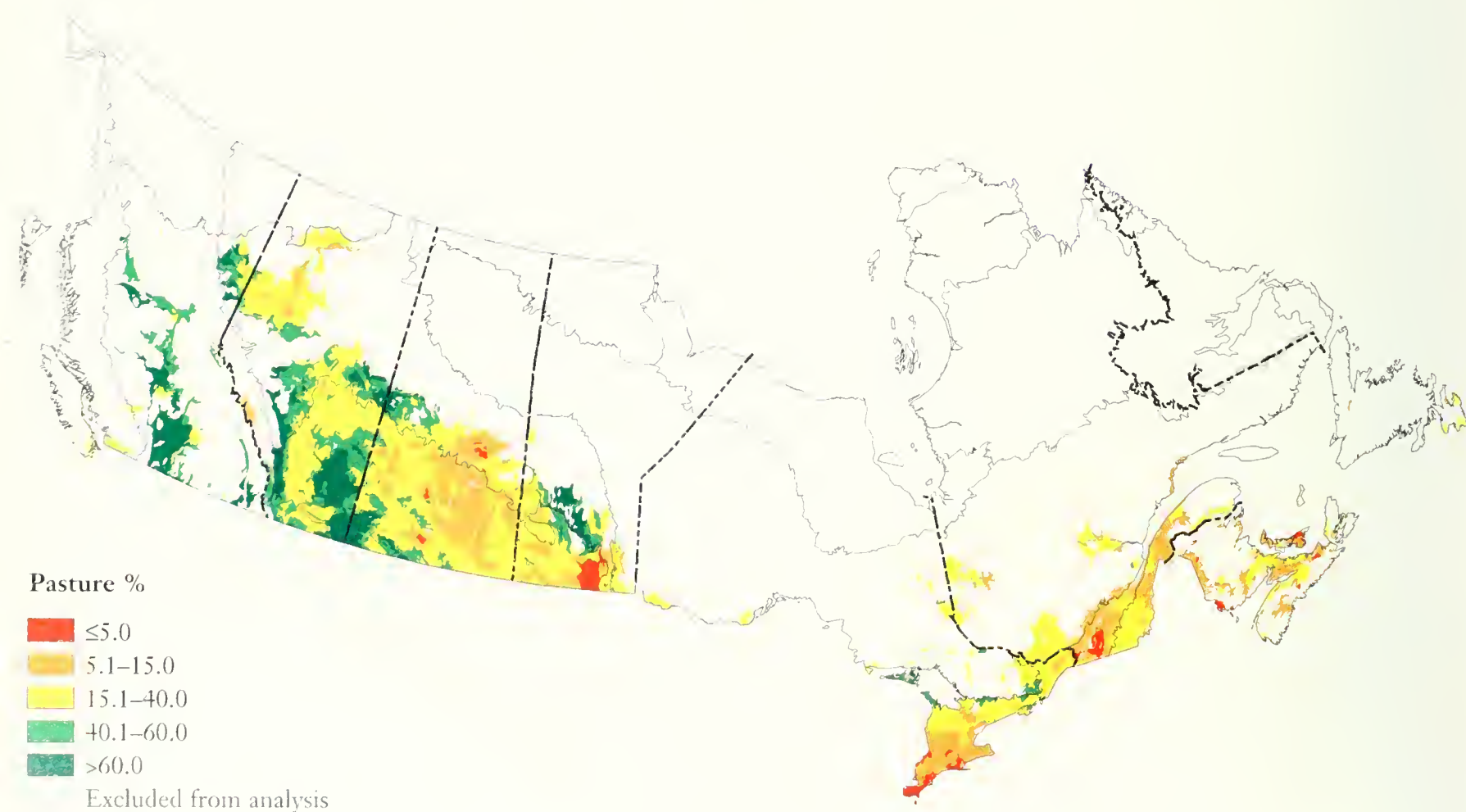
Figure 2

Pasture (improved and unimproved) as a proportion of farmland in 1996. (F. Wang and D.B. Gleig, AAFC)

Annual crops %

- ≤20.0
- 20.1–40.0
- 40.1–70.0
- >70.0
- Excluded from analysis
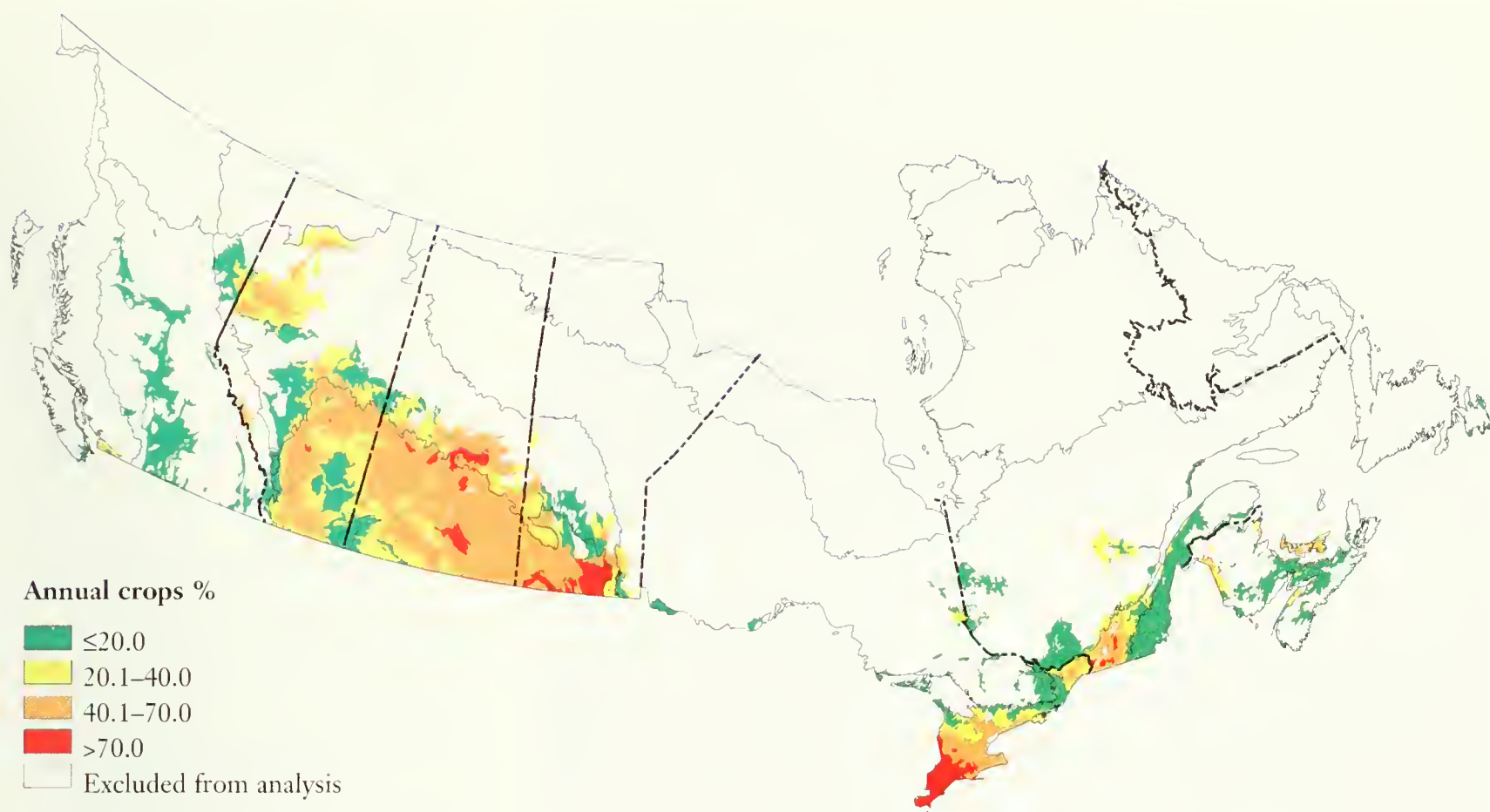
Figure 3

Annual crops as a proportion of farmland in 1996. (F. Wang and D.B. Gleig, AAFC)

Units per ha

- ≤0.05
- 0.06–0.15
- 0.16–0.30
- 0.31–0.60
- >0.60
- Excluded from analysis

Figure 4

Distribution of livestock in Canada in 1996. One animal unit is the quantity of livestock that produces manure containing 170 kg of N per year. For example, approximately 2 dairy cows are equivalent to 1 animal unit. (F. Wang and D.B. Gleig, AAFC)

The greenhouse effect

The earth is warmed by the sun's radiation (including visible light) that strikes it. The earth, in turn, radiates energy back into outer space, but this outgoing radiation differs from that of the sun: it has a longer wavelength and is invisible to the human eye. Furthermore, some of this outgoing, long-wave radiation is absorbed by various gases in the air, thereby warming the atmosphere. This warming is referred to as the "greenhouse effect" (though the warming effect inside glasshouses is really quite different!). The warming from the greenhouse effect is highly beneficial; without it, the average temperature on our planet would be about 33°C colder, making the earth inhospitable.

The gases causing the warming of the atmosphere are known as "greenhouse gases." The most important are water vapor, CO_2, CH_4, N_2O, and CFCs. Foremost among these is water vapor because it is a powerful absorber of long-wave radiation and is present in relatively high concentration. This gas, however, is already present in high enough concentration in the lower atmosphere that further increases in its concentration would have minimal effect on temperature.

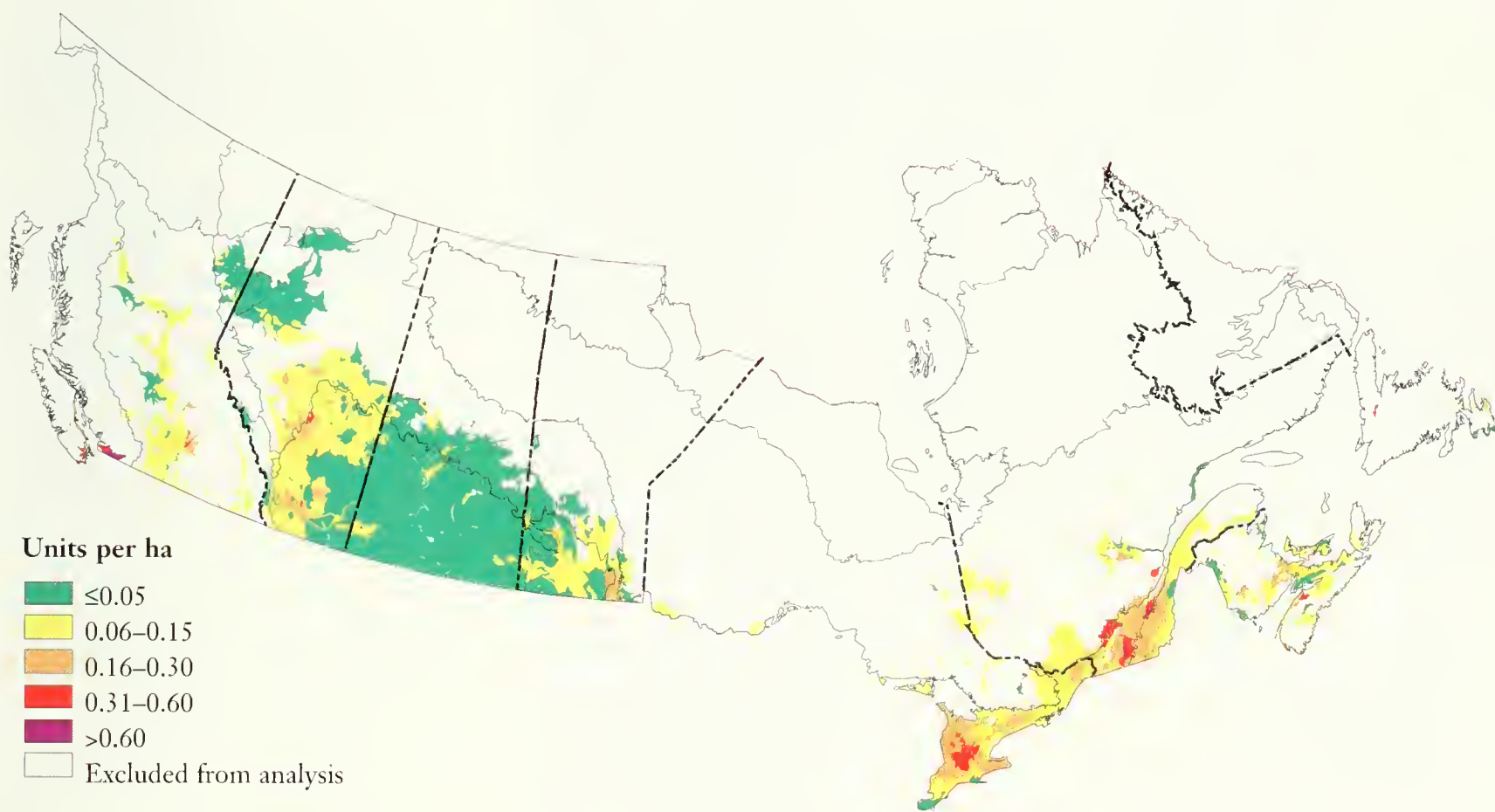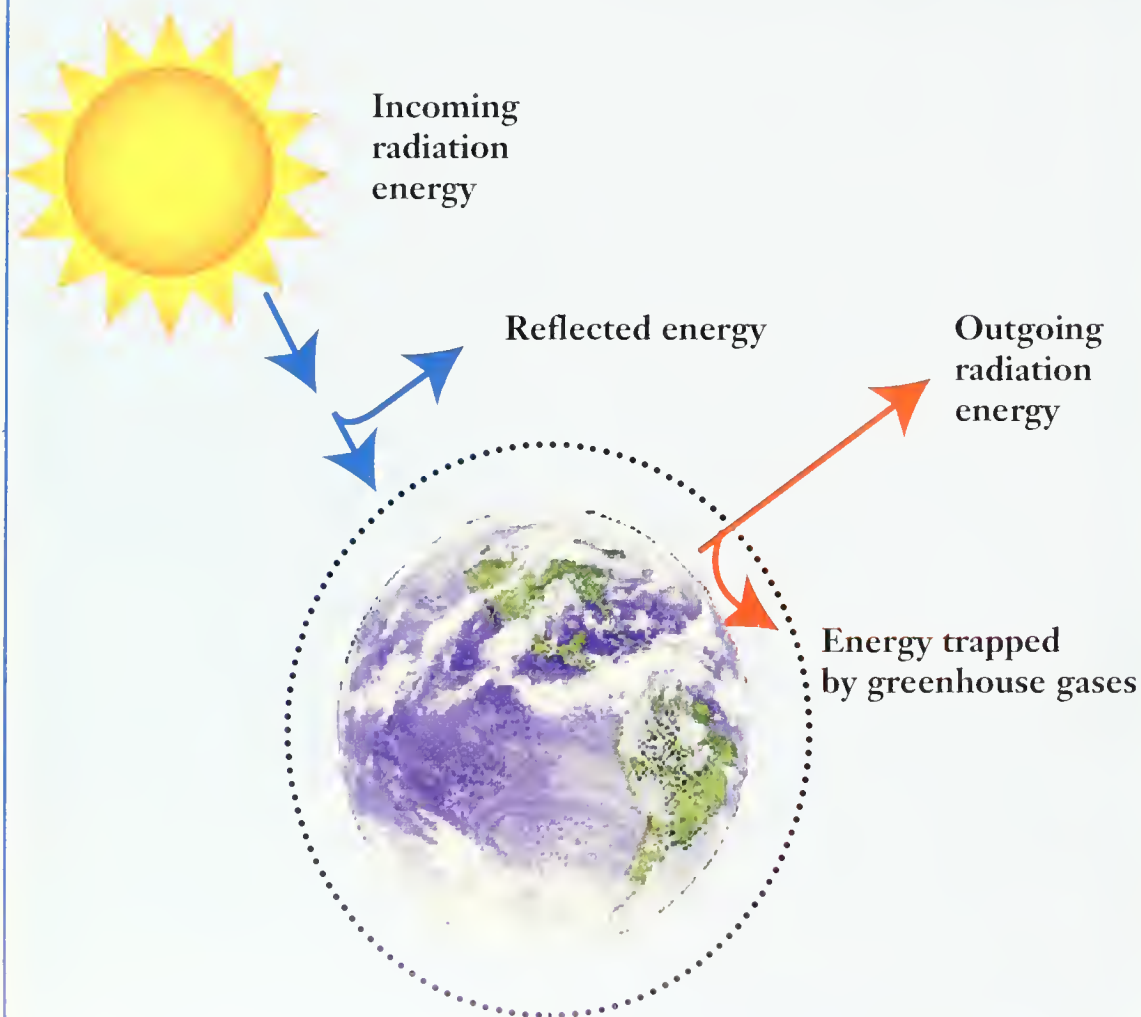Much of the current concern about greenhouse gases has arisen from the recent recognition that the concentration of other greenhouse gases—CO_2, CH_4, N_2O, and CFCs—has been increasing steadily since the industrial revolution, almost certainly because of human activity. By 1992, CO_2 had increased by 30%, CH_4 by

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Table 1 The area of farmland in Canada occupied by annual crops (million ha)

	1981	1986	1991	1996
Total farmland	65.9	67.9	67.7	68.0
Croplands	31.0	33.2	33.5	35.0
Summer fallow	9.7	8.5	7.9	6.3
Improved pasture	4.4	3.6	4.1	4.4
Nonimproved pasture	20.8	22.6	22.2	22.3

The "greenhouse effect"

Short-wavelength radiation emitted from the sun is absorbed by the earth and re-radiated at longer wavelengths. Carbon dioxide, CH_4, and N_2O account for 90% of this "greenhouse effect." In the long term, incoming radiation is balanced by outgoing radiation. Because of the greenhouse effect, the average surface temperature of the Earth is about 15°C, instead of –18°C.

Incoming radiation energy

Reflected energy

Outgoing radiation energy

Energy trapped by greenhouse gases

145%, and N_2O by 15%. Current rates of increase are 0.5% per year for CO_2, 0.6% for CH_4, and 0.3% for N_2O. The CFCs were not even present in the atmosphere until a few decades ago. If the current rates of increase continue, many scientists expect significant impact on the world's climate. For example, the Intergovernmental Panel on Climate Change predicts that the doubling of the CO_2 concentration, likely to happen in the 21st century, would increase average global temperatures by 1 to 3°C—a rate of warming unprecedented in the last 10 000 years. As well, the enhanced greenhouse effect could amplify climate variability.

In short, greenhouse gases have a desirable effect, as they warm the atmosphere and create favorable conditions for biological activity. Further increases in these gases, however, may lead to an "enhanced greenhouse effect" with uncertain, possibly disruptive, consequences.

Commitments to reduce emissions

Concern about the enhanced greenhouse effect has prompted international action to reduce emissions. A first agreement, intended to stabilize emissions at 1990 levels by 2000, was signed in 1992 at the Earth Summit in Rio de Janeiro. A more binding agreement was reached at Kyoto, Japan in 1997. This protocol was aimed at reducing emissions from participating countries to at least 5% below 1990 levels, by 2008 to 2012. This treaty will come into effect, however, only when ratified by at least 55 countries representing 55% of total

The Intergovernmental Panel on Climate Change

In 1988, the World Meteorological Organisation and the United Nations Environment Programme created the Intergovernmental Panel on Climate Change (IPCC). The IPCC evaluates research and policy options and publishes reports on climate change and the risk of global warming.

The latest synthesis report, based on 1995 science, includes the following conclusions:

- The balance of evidence from observed changes suggests a discernible human influence on global climate
- Human-induced climate change represents an important additional stress, particularly to the many ecological and socioeconomic systems already affected by pollution, and nonsustainable management practices
- Significant reduction in net greenhouse gas emissions are technically possible and can be economically feasible . . . in all sectors including . . . agriculture

The assessment report now being planned will provide the major science input to the future evolution of the UN Framework Convention on Climate Change and the Kyoto protocol.

The Kyoto protocol

At Kyoto, developed countries agreed to reduce their combined emissions of greenhouse gases by 5.2% from 1990 levels. This target will be realized through national reductions of 8% by Switzerland, many Central and East European states, and the European Union; reductions of 7% by the United States; and reductions of 6% by Canada, Hungary, Japan, and Poland. Russia, New Zealand, and Ukraine are to stabilize their emissions, while Norway may increase emissions by 1%, Australia by up to 8%, and Iceland by 10%.

The protocol aims to lower overall emissions from a group of six greenhouse gases by 2008–2012, calculated as an average over these 5 years. Cuts in the three most important gases—CO_2, CH_4, and N_2O–will be measured against a base year of 1990. Cuts in the three long-lived industrial gases—hydrofluorocarbon, perfluorocarbon, and sulfur hexafluoride—will be measured against either a 1990 or a 1995 base year, depending on what year is most beneficial.

greenhouse gas emissions from developed countries.

In the Kyoto protocol, Canada agreed to reduce its emissions to 94% of 1990 levels by 2008 to 2012. But Canada's emissions are already well above 1990 levels. Based on increases from 1990 to 1997 and assuming a "business as usual" scenario thereafter, one estimate suggests that Canada will need to reduce its emissions by about 21%. Consequently, a widespread effort involving all sectors of our economy will be required to meet Canada's commitments.

In 1992, Agriculture and Agri-Food Canada initiated a research program to estimate emissions of greenhouse gases from Canadian agriculture and to devise ways of reducing these emissions. Findings from this effort, some of which are summarized in this report, may help Canada meets its reduction target.

Estimates of emission

Carbon dioxide

The global carbon cycle

There are about 40 000 petagrams (Pg) of C in global circulation (Fig. 5). Most C is in the oceans but large pools also occur in soils, vegetation, and the atmosphere. Of these three pools, the atmosphere is the smallest but most active. The CO_2 in the air is continually being removed by plants through photosynthesis and being absorbed into the oceans. At the same time, however, CO_2 in the air is being replenished by release from plants, soils, and oceans. Thus, though C is always cycling, the concentration of atmospheric CO_2 has remained constant from year to year. Analysis of air bubbles trapped in old glaciers and shells buried in ocean sediments reveals that the atmospheric concentration of CO_2 had stayed at about 270 parts per million by volume (ppmv) for about 10 000 years.

Soil carbon map of Canada

The Canadian Soil Organic Carbon Database, consisting of over 15 000 soil landscape polygons, contains information describing the soil landscape and carbon content of each polygon. The total carbon in the first metre of all Canadian soils is 260 Pg (billion tonnes), which represents 13% of the world's total organic carbon. However, most of the carbon is in the northern wetlands and permafrost. Only about 10 Pg (billion tonnes) or 4% of the carbon is contained in the soil of agricultural ecosystems.

Total Soil Organic Carbon Content
CANADA

< 1.7 kg/m^2	41 - < 70 kg/m^2
1.7 - < 4.9 kg/m^2	70 kg/m^2 and over
4.9 - < 14 kg/m^2	Ice
14 - < 41 kg/m^2	Rock

(C. Tarnocai, AAFC)

760 CO$_2$ (Pool size in Pg)

610

1580 Soil

39 × 10³
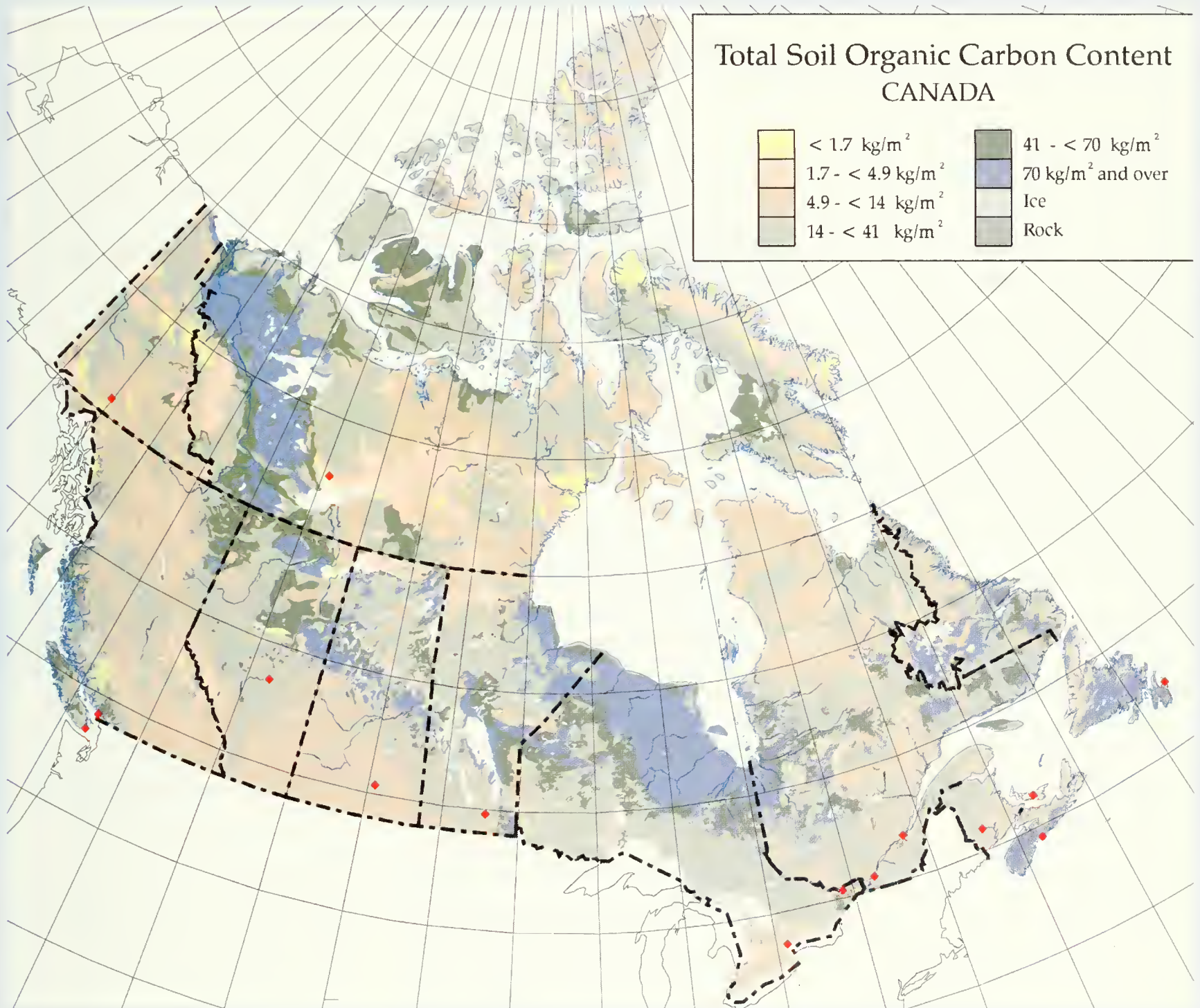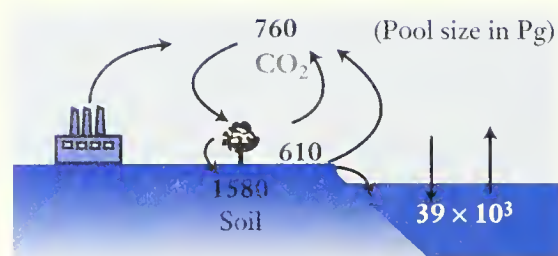
Figure 5

A simplified view of the global carbon cycle.

That changed with the advent of the Industrial Revolution. Since then, the demand for energy has resulted in ever-increasing amounts of fossil fuels being extracted from deep reserves and converted to atmospheric CO_2. This process, in effect, withdraws C from an inactive pool and emits it into the atmosphere as CO_2. Other activities have also favored increases in atmospheric CO_2: removal of forests has resulted in vegetative C being converted to CO_2, and the cultivation of previously undisturbed soils has resulted in soil C being converted to CO_2. Because of these processes, the emissions of CO_2 into the atmosphere now exceed the withdrawals, resulting in the gradual buildup of CO_2 (Fig. 6)
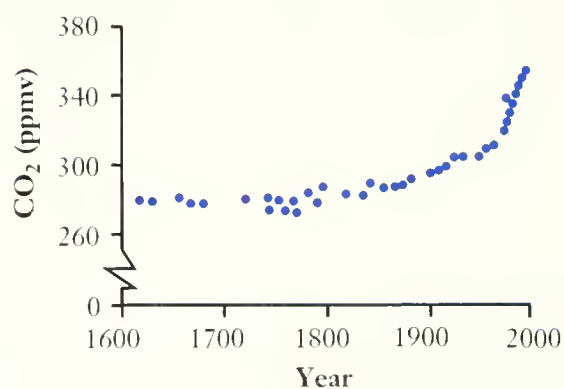
Figure 6

Long-term atmospheric CO_2 concentrations as determined from ice core data (before 1950) and atmospheric measurements (after 1950).

In 1995, fossil fuel combustion alone released 23.5 Pg (billion tonnes) of CO_2 into the atmosphere. The natural C cycle can absorb some of this increased CO_2 emission: some is absorbed by oceans, some by increased photosynthesis in plants. Nevertheless, the total amount of CO_2 in the atmosphere is still increasing by about 11.7 Pg (billion tonnes) of CO_2 every year. These increases are readily apparent in weekly measurements of atmospheric CO_2 at Alert, NWT, which, despite seasonal variations reflecting plant growth, show a clear, undeniable upward trend (Fig. 7).
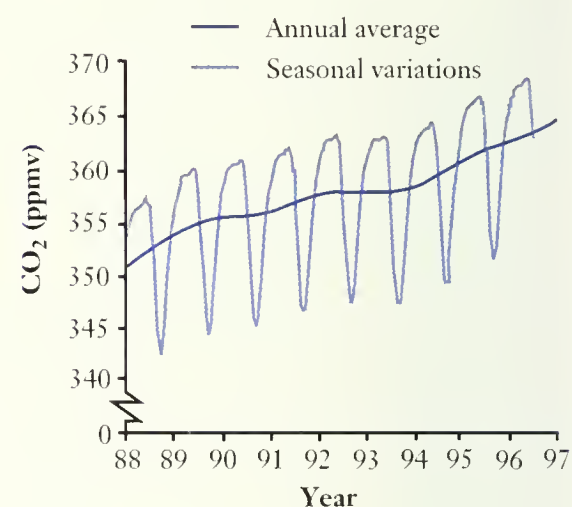
Figure 7

Seasonal variations of CO_2 concentrations measured at Alert, NWT. Most land and, therefore, vegetation on the earth is in the Northern Hemisphere. This vegetation draws heavily on the atmospheric CO_2 pool in summer but returns the CO_2 as the vegetation dies in winter.

Carbon cycles in agricultural ecosystems

The carbon cycle in cropped land is quite simple, at least in principle (Fig. 8). Carbon dioxide is absorbed from the atmosphere by plant leaves and is transformed, via photosynthesis,

into C-containing compounds such as sugars, carbohydrates, cellulose, and lignin. Some of this material is used by the plant for its own energy and converted back to CO_2. Of the C remaining in the plant, a portion is removed during harvest (e.g., in grain) and the rest is returned to the soil. This residue, including roots, becomes part of the soil organic matter. Microorganisms in the soil, in turn, decompose the soil organic matter, releasing CO_2 back into the atmosphere and closing the loop. This cycle is essentially the same in all cropping systems, but rates vary depending on climate, soil, and crop type.
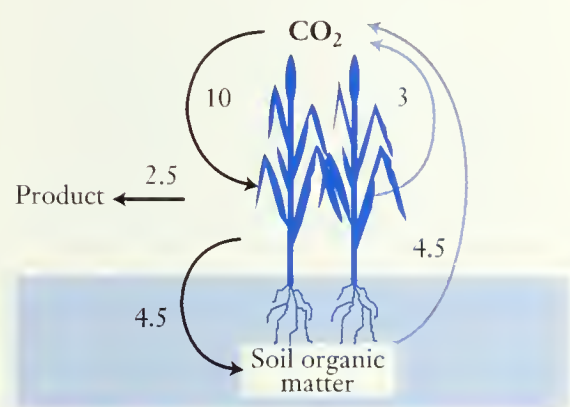
Figure 8

Conceptual C cycle for corn (values are estimates of annual flows of C in Mg/ha).

Where present, livestock add another component to the carbon cycle (Fig. 9). Instead of being exported, much of the harvested plant material is fed to animals or used as bedding. Some of this C is released by the animals to the atmosphere as CO_2, some is removed as animal products, but much is returned to the soil as manure. Consequently, livestock-based systems often retain higher proportions of C on the farms. In many ways, this cycle does not differ

from that in crops grown for human food. But the CO_2 and wastes from human consumption of crops are often released far from the farm and therefore are not usually thought of as part of the agricultural C cycle.
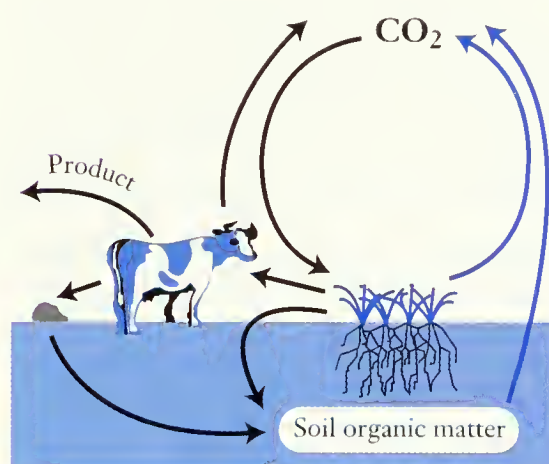
Figure 9

Conceptual C cycle of a livestock-based cropping system.

In systems that have remained largely unchanged for several decades, the amount of C entering the soil as plant residues is usually balanced by the amount of C converted to CO_2 by microbial activity. Consequently, though C is continually added to the soil, the amount of C stored in the soil may not change measurably. For example, in the corn system illustrated (*see* Fig. 8), residue inputs of 4.5 Mg (tonne) C per hectare are exactly balanced by microbial production of CO_2 from the soil, so that there is no change in the amount of C stored in the soil.

Management effects on carbon cycle

A change in the way land is managed can disrupt the C cycle, affecting the amount of C stored. Perhaps the most

drastic example was the initial cultivation of soils for farming. This event, which happened on many Canadian farmlands more than a century ago, resulted in high losses of soil C: many soils lost about 25% of the C originally present in the C-rich surface layer, releasing a lot of CO_2 into the atmosphere. There are several reasons for this loss. First, farming involves the harvest of C from the fields, and the removal of this C means less input of new C. As well, cultivation and growing annual crops often speed up the conversion of soil C to CO_2 by soil microbes. After soils have been cultivated for a few decades, however, losses of C usually slow down or cease entirely, and the level of soil C is again stable (Fig. 10).
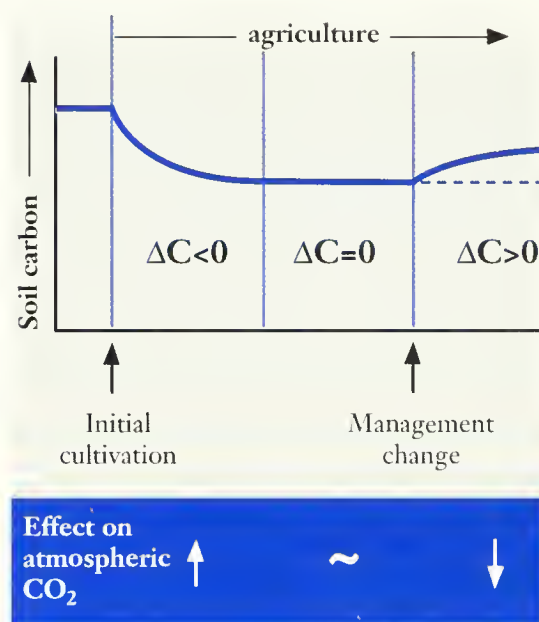
Figure 10

Theoretical changes in soil C as influenced by management.

The effect of the initial cultivation on the C cycle is largely past. Today we are interested more in how current practices or future modifications might affect the C cycle. By choosing their crops, tillage practices, fertilizer treatments, and other options, farmers can alter the C cycle, thereby changing the amount of C stored in the system.

Measuring management effects on carbon cycle

How do we determine the influences of farming practices on the C cycle? One way is to measure all the flows in the C cycle in a farm field (*see* Fig. 8). By subtracting the amounts of C leaving the field from the amounts entering, we can calculate the net change in C. Such measurements are useful in describing how management affects the C cycle, but they are time-consuming and are used only at selected research sites.

Another way is to measure the net exchange of CO_2 between vegetation and the atmosphere above it. Using sensors placed on towers, researchers can measure CO_2 transfer above the crop continuously for months or even years, allowing them to calculate CO_2 exchange over an entire field. This approach, using towers, aircraft, and other variations, provides an average of net CO_2 emissions from larger areas, thereby overcoming the natural variations that occur across a field. The main disadvantage of this method is cost and the difficulty of integrating over long periods.

A third method, and that most widely used, is to measure the change in the amount of stored C after a number of years. In farm fields (as opposed to forests), virtually all the C is stored in the soil organic matter. By measuring the amount of soil C once and then again several years later, scientists can tell whether the field has gained or lost C under certain practices (Fig. 11).

A common variation on this approach is to measure the change under one treatment relative to another. For example, if we are interested in the effect of tillage on C storage, we can maintain two systems side by side—one tilled, the other not—and then measure the increase in stored C in the untilled plot by comparing it to that in the tilled plot. But measuring changes in soil C is not easy. Any increase may be small, say 3 tonnes C per hectare, compared to the amount initially there, say 60 tonnes C per hectare. This problem is further complicated by the natural variability of C in the field, which is often much greater than the difference we hope to measure. Accurate measurement of soil C change, therefore, requires careful sampling and analysis. Some researchers have focused on specific forms of soil C or on atomic markers (isotopes) to measure soil C changes more precisely.
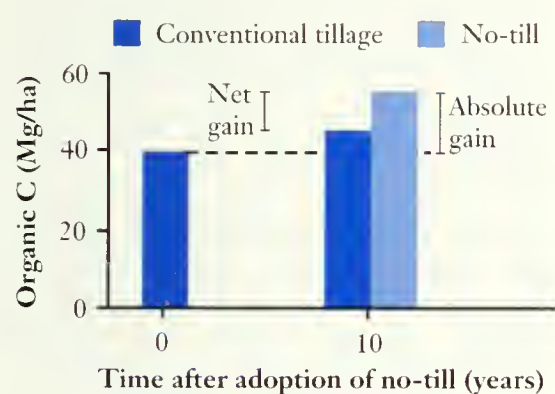
Figure 11

Estimating soil C gain after adoption of no-till.

To estimate the effects of management on the C cycle over large regions, we have to rely on models. These models may be simple equations or highly complex computer programs that take into account many variables such as

Tower-based flux measurements

Tower-based long-term measurements of CO_2, water vapor, and energy exchange from many ecosystems are now available for North America and Europe. Scientists make these measurements to

- collect critical new information to help define the global CO_2 budget
- improve predictions of future concentrations of atmospheric CO_2
- enhance understanding of CO_2 exchange between atmosphere and biosphere
- determine response of CO_2 fluxes to changes in environment and climate
- provide information on processes controlling CO_2 flux and net ecosystem productivity
- help calibrate and verify data for CO_2 flux models.

(S. McGinn and E. Pattey, AAFC)

Tower-based system for measuring gas exchanges.

Twin Otter aircraft

The Twin Otter aircraft (*see* photo), operated by the Flight Research Laboratory of the National Research Council, provides an excellent platform for investigating gas exchange near the surface. It is equipped with sophisticated turbulence and trace gas sensors. At a flying speed of 60 m/s and at altitudes of 30–100 m, the instruments record atmospheric data every 2 m. In flight, the measured net fluxes of a particular gas, such as CO_2, water vapor, O_3, CH_4, and N_2O, can be determined as the average product of vertical wind and the actual concentration of the gas. The flux value can be positive (indicating that more gas is released by the surface than is being absorbed), zero, or negative (meaning that more gas is being absorbed than is being released).

(J.I. MacPherson, NRC, and R.L. Desjardins, AAFC)

Get a feel for magnitudes

Multiplier	Name	Other name	Abbreviation
10^0 gram			g
10^3 grams	kilogram		kg
10^6 grams	megagram	tonne	Mg
10^9 grams	gigagram	thousand tonnes	Gg
10^{12} grams	teragram	million tonnes	Tg
10^{15} grams	petagram	gigatonne or billion tonnes	Pg

100 m × 100 m = 1 hectare (ha).
1 ha = 2.5 acres.

weather, soil type, and farming practices to predict C processes on the farm. Whatever their complexity, these models need to be checked against actual measurements to ensure that they are reliable. By using measurements from specific locations, researchers can verify the models and present their predictions for large areas with some confidence.

Examples of management effects on carbon cycle

Scientists have measured the effect of management on the C cycle at numerous sites across Canada. Rather than attempt to summarize all these, we offer a few as examples of recent findings.

Crop rotation in forest soil

The Breton plots near Edmonton, Alta., are among the longest-running research sites in Canada. This experiment shows that an appropriate crop rotation, including legumes and cereal crops, can result in large increases in the C content

of this soil, originally cleared from forest (Fig. 12). By comparison, soil under fallow–wheat showed no appreciable gains of C. Within each crop rotation, soil receiving fertilizer had higher gains of C than unfertilized soils, probably because of higher residue inputs with fertilization. Manure application increased soil C even more than fertilizer, because the manure not only increased crop yield but also provided direct addition of C.
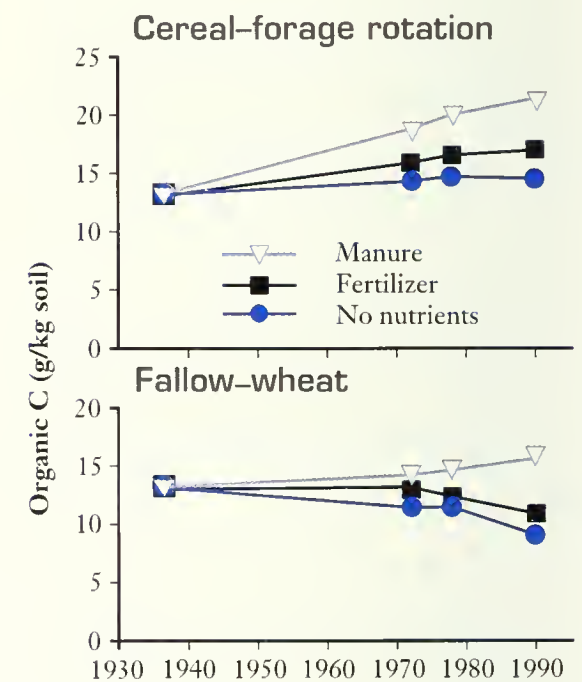
Figure 12

Change in organic C in two cropping systems at Breton, Alta., as affected by nutrient application. (R.C. Izaurralde, University of Alberta)

Fertilizer application to corn

Application of fertilizer can increase soil C. At a long-term research site in Ontario, soil under fertilized corn had higher soil C than that under unfertilized corn after 32 years (Fig. 13). Using C isotopes to distinguish between C from corn and that from previous organic matter, the researchers also showed that the increase came entirely from the corn

residue—fertilization had no effect on the organic matter that was there before corn was first planted. Adding fertilizer to this soil increased yields, thereby increasing the amount of residues returned to the soil. Where there is no yield response to fertilizer, there may be no increase in soil C.
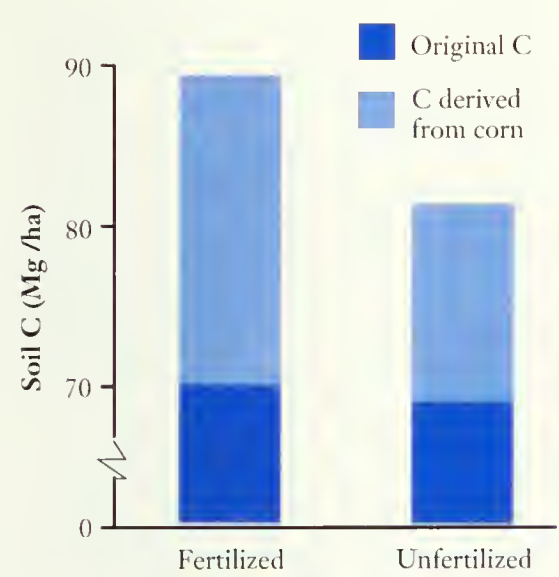
Figure 13

Soil C after 32 years of growing corn showing the proportion derived from corn and that remaining from previous organic matter. (E. Gregorich, AAFC)

Tillage

Historically, tillage was one of the main tools available to farmers for controlling weeds and preparing land for seeding. But with new herbicides and seeding equipment, intensive tillage is no longer always necessary. Some farmers have opted to eliminate tillage entirely, a practice referred to as "no-till" farming or "direct seeding." This practice can lead to substantial increases in soil C. A partial survey of studies across Canada shows no-till can increase soil C by as much as 10 Mg (tonne) per hectare, when compared

Soil management

Some of the many techniques used by farmers include
- Conventional tillage: soils are routinely cultivated to eliminate weeds and prepare soil for seeding
- Reduced, minimum, or conservation tillage: tillage is reduced to keep residues on the surface
- No-till: seeds are planted directly without any prior tillage; weeds are controlled by chemicals
- Summer fallow: no seeding for one season; weeds are controlled by cultivation or by chemicals.

Definitions of tillage practices differ from region to region.

No-till can have several advantages. It requires less time and machinery. The organic residues left on top of the soil help to preserve moisture and protect it against erosion.

Use of no-till* in Canada

	Area under no-till (%)	
	1991	1996
Atlantic	2	2
Quebec	3	4
Ontario	4	15
Manitoba	5	8
Saskatchewan	10	20
Alberta	3	9
British Columbia	5	9
Canada	7	14

* No-till includes direct seeding into stubble or sod, or tillage of only the ridge of rows.

Table 2 Examples of the effects of no-till on soil C in selected long-term studies in Canada

Location	Duration (years)	Cropping system	Soil C gain/loss* (Mg/ha)
Ontario	11	Corn	-0.9
Ontario	18	Corn–soybean	11.5
Saskatchewan	11	Wheat	1.8
Saskatchewan	11	Fallow–wheat	0.6

*C in no-till - C in tilled.
Tilled treatments and depth of analysis vary among sites.
(C. Campbell, AAFC; C. Drury, AAFC; T. Vyn, University of Guelph)

Summer fallow in Canada

The major development that allowed agriculture in the climatically restricted prairies occurred by accident. In the spring of 1885, the farm horses of Indian Head, Sask., were conscripted for the army that was suppressing the Rebellion. By the time the horses were released, it was too late to plant. However, the land was worked during the summer and produced an excellent crop the next year, while drought caused an almost complete crop failure everywhere else. Experiments at the Dominion Experimental Station at Indian Head, established soon after, led to the system of summer fallowing being developed that turned Palliser's Triangle into the bread-basket of Canada. (Palliser's Triangle is the dry southwestern area of Alberta and Saskatchewan, named after this early explorer.) With modern methods of weed control, fertilization, and planting, summer fallow is no longer as essential as it once was.

Fields not cropped for a year still require weed control, either mechanical or chemical. The bare soil is directly exposed to wind and sun, enhancing erosion and organic matter decomposition. Without a crop, little organic residue is returned to the soil. Use of summer fallow depends on soil moisture and expected crop income. It is expected that summer fallowing will continue to decrease and stabilize at about 4.5 million hectares by about 2050.

Area of summer fallow in Canada

with tilled soil (Table 2). But such gains are not automatic. In some cases, researchers were not able to detect any effect of tillage on soil C. The inconsistency of the results is not surprising, because the response of soil C is affected by climate, soil properties, length of time under no-till, crop rotation, and many other factors. Some of the variability may simply reflect the difficulty of measuring soil C change precisely.

Summer fallow

Summer fallow, the practice of leaving land unplanted for a whole year, was once widely practiced in western Canada because it helped control weeds, replenish soil moisture, and increase available nutrients in the soil. The area of fallow has declined recently but still occupies about 6 million hectares every year. Soils that are frequently under summer fallow usually have lower C content than those that are cropped annually. For example, long-term studies in Saskatchewan show that, after several decades, soil cropped to wheat every year have C contents several tonnes per hectare higher than those that are fallowed every second year (Fig. 14). Fallow has two negative effects on soil C: it hastens decomposition of soil C, and it reduces C inputs into the soil during the year when there is no crop.

Figure 14

Organic C in surface soil of fertilized fallow–wheat (FW) and continuous wheat (W) in long-term sites in Saskatchewan.
(C. Campbell, AAFC)

Grass on previously cultivated land

One of the fastest ways to increase soil C is to return cultivated land to vegetation like that under "native" conditions. A study at Lethbridge, Alta., compared the C cycle in four treatments: native grasses, crested wheat grass (a common, introduced grass), continuous wheat (wheat planted annually), and fallow–wheat (wheat planted only every second year). These plots were started on land that had been under fallow–wheat for many decades. Using the C budget method described earlier, researchers showed that the grass plots were gaining large amounts of C (Table 3). The fallow–wheat plots, on the other hand, were losing C whereas the continuous wheat plots were neither losing nor gaining C.

Manure application to silage corn

Animal manure is widely used as a nutrient source for crops. In a study at St-Lambert, Que., regular manure application increased the amount of C stored in the soil after 10 years (Table 4). Part of this increase came from the direct addition of C in the manure. This C represents a recycling of the C from plant materials used to feed and bed the animals. But the manure, by providing plant nutrients and improving soil aggregation and porosity, also increased crop growth and the amount of C returned to the soil as residues. Thus, using manure not only results in efficient recycling of plant C but also promotes soil C gains by increasing plant photosynthesis.

These few examples, along with numerous similar studies across Canada, show clearly that the choice of farming practice can affect the C cycle and influence the net exchange of CO_2 from farms.

Table 3 Carbon balance on plots seeded to grass or wheat in Lethbridge

	Crested wheatgrass	Native grasses	Continuous wheat	Wheat–fallow
			g/m^2	
Net primary production	423	315	291	215
Harvested matter	-101	-66	-76	-58
Carbon input in the soils	322	249	215	157
Carbon loss from the soils (organic matter decay)	-191	-196	-207	-178
Net soil carbon gain (loss)	131	53	8	-21

(B.H. Ellert, AAFC)

Table 4 Carbon inputs, soil carbon storage, and soil physical properties of a silty clay loam in Quebec following 10 years of biennial applications of solid dairy cattle manure

Manure application rate (t/ha/2 y)	C added by manure (kg/ha/y)	C added by crop (kg/ha/y)	Soil C storage (kg /ha)	Aggregate size (mm)	Porosity (%)
0	0	350	4969	1.3	51
20	870	380	6078	1.6	52
40	1740	430	6459	1.5	54
60	2610	480	7080	1.7	55
80	3480	530	7505	1.7	56
100	4350	600	7708	1.8	56

(A. N'Dayegamyie, MAPAQ, Qc and D. Angers, AAFC)

Energy use

Most cropping systems depend on external energy sources. Much of this energy comes from the burning of fossil fuels, which releases CO_2 into the atmosphere. We must consider this CO_2, which is part of the C cycle on farms, if we want to look at the overall effect of agriculture on the atmosphere.

The main use of fuel on Canadian farms is to power the machinery for tillage, planting, harvesting, and other field operations. Additional amounts are also used for transportation, irrigation, drying of crops, heating of buildings, and equipment used in livestock operations.

Aside from that used directly on the farms, agriculture also depends on energy for the manufacture and transport of inputs. For example, manufacturing pesticides, buildings, and farm machinery uses energy. But the largest off-farm use of energy is for making and transporting fertilizer, notably that containing nitrogen. The resulting release of CO_2 varies depending on fertilizer form (Table 5). But, on average, producing and

Table 5 C released as CO_2 from manufacturing and transporting fertilizers

Fertilizer	kg C per kg of nutrient (N,P,K)
Anhydrous ammonia	0.8
Urea	1.2
Ammonium nitrate	1.1
Ammonium sulfate	1.0
Urea–ammonium nitrate	1.1
Monoammonium phosphate (N + P)	1.2
Potassium (K$_2$O)	0.2

(E. Coxworth, Saskatoon, Sask.)

transporting 1 kg of fertilizer N releases about 1 kg of C (or 3.7 kg CO_2) into the atmosphere. In national estimates of emissions, researchers usually assign these indirect uses of energy to other sectors (e.g., manufacturing). But they still relate to farming and offer a means of reducing CO_2 emissions from farms.

The rate of CO_2 emission from energy use on Canadian farmland varies widely, depending on how intensive the farming operation is. For example, farms producing livestock on grassland may require relatively little external energy. By comparison, farms with high inputs of fertilizer, intensive tillage, and irrigation may generate high amounts of CO_2 from using energy.

A typical farming system on cropland may release C from energy use at a rate of roughly 100 kg C per hectare per year. For example, an analysis of farming systems at Indian Head, Sask., showed that the total C emission from direct and indirect use of energy ranged from about 100 to 115 kg C per hectare per year, depending on tillage intensity (Fig. 15). The largest sources of this CO_2 were the manufacture and transport of fertilizer and the on-farm use of fuel.

The net effect of a farming system on atmospheric CO_2 is the increase in soil C minus the amount of C released from energy use. Thus, a farm that emits CO_2 from fuel use at a rate of 100 kg C per hectare per year will have a net benefit on atmospheric CO_2 only if the rate of soil C gain exceeds 100 kg C per hectare per year. For example, suppose a field gains 4 Mg (tonnes) C per hectare over several decades in response to better

management and that soil C then stabilizes at that new, higher level. The net benefit to the atmosphere will be the difference between the soil C gain and cumulative CO_2 release from energy use (Fig. 16). If CO_2 from energy use is 100 kg C per hectare per year, then the CO_2 release would be equal to the soil C gain after about 40 years. Thereafter, the field would again be a net emitter of CO_2, unless some further soil C gains are made.
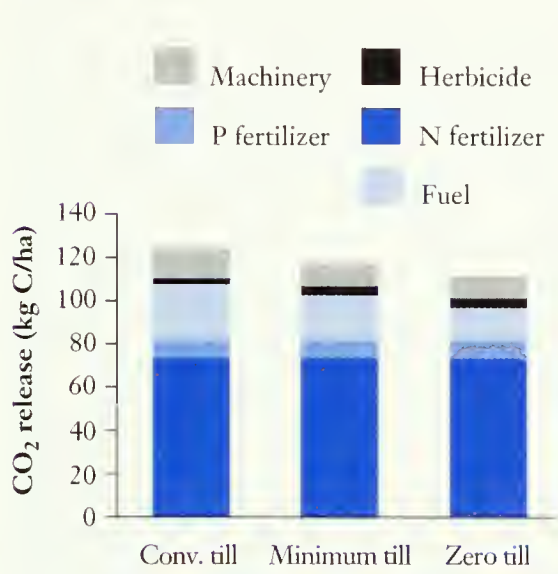
Figure 15

Sources of CO_2 from spring wheat at Indian Head, Sask., as affected by tillage. (E. Coxworth, Saskatoon, Sask.)
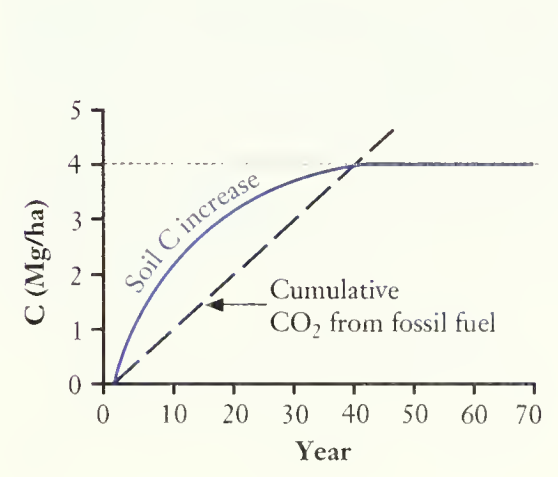
Figure 16

Conceptual illustration of soil C gain and cumulative CO_2 from fossil fuels in an agroecosystem.

because soil properties and management practices vary across the country. Measuring the change directly would require enormous effort, so our estimates rely on mathematical models.

In a recent study, a detailed model ("Century") was used to predict changes in C content of Canadian agricultural soils, based on climate and soils data from across Canada. Information about farming practices was taken from recent Statistics Canada data. The study considered the predominant agricultural systems in Canada but did not include all possible variations. Some of the factors not included were a) biomass burning, a practice no longer widely used; b) soil erosion, which moves C around the landscape; c) manure addition; d) minor crops such as potatoes and annual legumes; and d) minimum tillage, which is intermediate between "conventional" and no-till. Future analyses may include some of these factors.

The model predictions agree with historical observations: soil C declines rapidly after initial cultivation, but the rate of decline diminishes gradually over time as soils approach a new "steady-state" at which they no longer lose C (Fig. 17). According to the model, current rates of C loss are negligible. The model predicts, further, that agricultural soils will begin regaining some of the lost C in the future, as farmers adopt improved practices such as no-till and reduced summer fallow (Table 6). According to the model, the agricultural soils were losing C at a rate of about 3 Tg (million tonnes) of C per year in 1970 but could be gaining C at a rate of 0.4 Tg of C per year by 2010. Predicted rates of soil C change differ among

Estimates of carbon dioxide emissions in Canada

Scientists calculate the net emissions of CO_2 from Canadian agriculture by estimating the annual change in stored C and adding CO_2 release from fossil fuel (*see* Fig. 8). Most of the C stored in agroecosystems occurs in soil, so they can estimate the change in storage from the gain or loss of soil C.

Estimate of soil C change

Estimating soil C change for all the agricultural area of Canada is difficult,

regions, reflecting variable adoption of improved practices and differences in soil properties. For example, the model suggests that rates of gain are highest in Saskatchewan and lowest in Alberta.
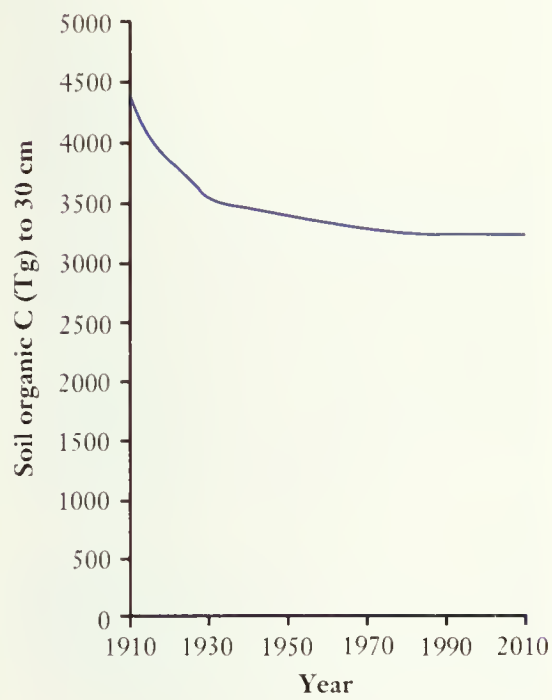
Figure 17

Long-term predictions of soil C change based on the Century model, assuming only a gradual adoption of no-till. (W. Smith, Ottawa, Ont.)

All these predicted rates of change are low compared to the total amount of stored C. For example, a C gain of 0.4 Tg/y amounts to a rate of <0.01 Mg (tonnes) of C per hectare per year, when averaged across all cultivated soils in Canada. This value is very small compared to the total C content of soils, which is commonly about 60–100 Mg (tonnes) C per hectare.

The Century model predictions represent our current best estimates of soil C change across the country. But these estimates rely on several simplifying assumptions and have not yet been fully tested for all conditions across Canada. For example, compared

Rate of change of carbon in Canadian agricultural soils, 1990

Agriculture's largest store of carbon is in its soils, where dead plants have accumulated over the centuries. Cultivating the soil, however, has greatly affected this store of carbon, reducing it by about 15–35%. Agriculture and Agri-Food Canada's research program confirmed that, in many cases, farmers have been able to reduce or even reverse the C loss with good management.

The Century model (a site-specific computer simulation of the dynamics of soil organic matter) was used to estimate the rate of change of carbon in Canadian soils for the year 1990. Soil, crop coverage, tillage, and crop rotation data were obtained for 1229 soil landscape of Canada polygons. Century runs were carried out on 15% of the polygons. For each sampled polygon Century was run for one to five types of crop rotations under conventional tillage. It was also run for no-till practices for polygons for which no-till represented 5% or more of the agricultural area. The map shows carbon change in agricultural soils on the Prairies during 1990. The estimated average carbon loss corresponds to about 40 kg/ha/y, which is much smaller than the amount that can be measured.

Rate of change in soil carbon in 1990 (t/ha)

(W. Smith, Ottawa, Ont.)

Table 6 Soil organic C change in Canadian crop lands[1] as estimated using the Century model

	1970	1981	1986	1991	1996
Average C change (kg/ha/y)	-67	-51	-48	-35	-11
Total C change (Tg/y)	-2.7	-2.1	-2.0	-1.4	-0.5

[1] Pastures are not included.
[2] Since 1910, there has been a 24% reduction of soil organic C (1053 Tg C) in cultivated soils. Total C in first metre of agricultural soils in Canada is 10 000 Tg. (W. Smith, Ottawa, Ont.)

Table 7 Estimated CO_2 emissions from fossil fuel use in Canadian agriculture

	1981	1986	1991	1996
		(Tg CO_2)		
Direct use				
Fuel used on farm	9.5	7.7	8.1	9.5
Indirect uses				
Fertilizer manufacture, transport & application	4.4	5.5	5.1	6.6
Machinery manufacture & repair	4.8	4.8	4.8	4.8
Building construction (steel & cement manufacture)	2.5	2.2	2.3	2.2
Pesticide manufacture	0.2	0.3	0.3	0.3
Electricity generation	1.8	1.9	2.1	2.4
Total indirect fossil CO_2	13.7	14.7	14.6	16.3

(R.L. Desjardins, AAFC; E. Coxworth, Saskatoon, Sask.)

to some actual data on the change in soil carbon under no-till, the predicted changes appear to be low by as much as 50%. With further research and as the reliability of the models improves, the estimates may be adjusted.

Emissions from the use of fossil fuel

The other major source of CO_2 in agriculture, aside from the biological C cycle, is burning of fossil fuel. Direct fuel use on Canadian farms releases about 10 Tg (million tonnes) of CO_2 annually (Table 7). Indirect sources, associated with the production or transport of inputs, emit additional CO_2. Of these, manufacture and transport of fertilizer is the most important. Emissions from this source have increased steadily because of increased rates of fertilizer application. The manufacture of farm machinery, construction of buildings, and generation of electricity also emit large amounts of CO_2. Altogether, CO_2 emissions from indirect sources amounted to about 16 Tg (million tonnes) of CO_2 in 1996.

Direct and indirect use of fossil fuels on Canadian farms, therefore, amounted to about 26 Tg (million tonnes) of CO_2 (7 Tg C) in 1996. In calculating national inventories, however, researchers count only the CO_2 produced from stationary combustion (about 3 Tg CO_2 in 1996) in estimates for agriculture; the remainder they include in emissions from manufacturing, construction, and transportation sectors.

Total emissions

Total emissions of CO_2 from Canadian agricultural activity are the sum of net soil C loss, emissions from direct use of fossil fuel, and emissions from

indirect uses of fossil fuel (Table 8). These estimates suggest that, in 1996, agricultural activity released about 28 Tg of CO_2 into the atmosphere, slightly less than in 1981. Projections to the year 2010 suggest that total emissions will not change appreciably from those in 1996. Scientists predict that emissions from soils are likely to decline and become negative (that is, soils will gain C) but, at the same time, emissions from indirect sources may increase, offsetting these benefits. These estimates, however, assume a "business-as-usual" scenario and do not yet take into account any benefits that might occur from concerted efforts to reduce emissions.

Table 8 Estimated CO_2 emissions from Canadian agriculture from direct and indirect sources

	1981	1986	1991	1996
		(Tg CO_2)		
Direct emissions				
Soils	7.7	7.3	5.1	1.8
Fuel used on farm	9.5	7.7	8.1	9.5
Total direct emissions	17.2	15.0	13.2	11.3
Indirect emissions	13.7	14.7	14.6	16.3
Total emissions attributable to agriculture	30.9	29.7	27.8	27.6

(R.L. Desjardins, AAFC)

Methane

Methane is perhaps most familiar to us as the main component of natural gas. Though present in the atmosphere at very low concentrations (about 2 ppmv), it is a comparatively powerful greenhouse gas: one kilogram of CH_4 has 21 times the warming effect of the same amount of CO_2, when calculated over a 100-year period. This effect arises not only from the CH_4 itself but also from other indirect effects, including the CO_2 to which it eventually converts.

The concentration of CH_4 in the atmosphere, which had been increasing at a rate of 1.1%, is now increasing at about 0.6% per year. Globally, agriculture is a prominent source of CH_4, accounting for about two-thirds of human-induced emissions.

Most of the CH_4 emitted from agriculture is produced by the microbial breakdown of plant material.

Normally, when oxygen supply is adequate, most of the C in decomposing plant material converts to CO_2. But, in the absence of oxygen, decomposition is incomplete and C is released as CH_4 instead. In agricultural systems, such conditions occur in the digestive system of ruminant livestock (e.g., cattle) and in water-logged soils (e.g., rice paddies). Incomplete burning of fuel or organic wastes also produces small amounts of CH_4. Methane and CO_2, therefore, are somewhat complementary: C not converted to CH_4 is largely released as CO_2.

The CH_4 emitted into the atmosphere has a lifetime of, on average, about 12 years. Chemical reactions in the atmosphere convert most CH_4 to CO_2. Microorganisms living in the soil convert probably less than 10% of CH_4 released into the atmosphere to CO_2.

Methane emission by livestock

All animals produce CH_4 when they digest feed. But emission is especially high from cattle, sheep, goats, and other ruminants. These animals have a rumen, or "fore-stomach," where microbial fermentation partially digests feed. Because of this process, ruminants can efficiently digest fibrous feeds. But, since the fermentation occurs under restricted oxygen supply, some C in the feed, often about 5–10%, is released as CH_4 rather than as CO_2 (Fig. 18). Nonruminant animals, such as pigs and poultry, also emit some CH_4 during digestion, but the amounts released are almost negligible by comparison (Table 9).
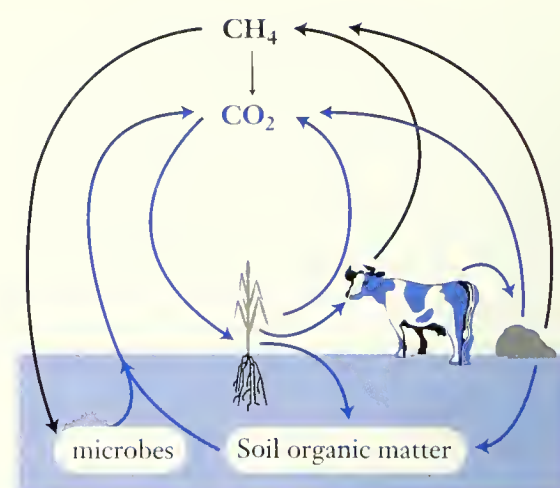
Figure 18
CO_2 and CH_4 flow in a livestock-based agroecosystem.

Measuring methane emission

We can measure the amount of CH_4 emitted by livestock in a number of ways. One method is to place the animal in an enclosed chamber and measure CH_4 accumulating in the airspace. This approach permits accurate analysis, but estimates may be distorted because the animal is removed from its normal environment. Recently, therefore, researchers have

Table 9 Estimated CH_4 emissions from livestock and manure in 1991

	Number of animals (Millions)	Mass of manure (Tg)	Methane from manure (Gg)	Methane from livestock (Gg)	Total methane (Gg)
Dairy cattle	2	17	70	190	260
Beef cattle	11	98	10	558	568
Pigs	10	19	102	15	117
Poultry	103	3	8	N/A	8
Sheep/lambs	1	0.4	0.2	8	8
Total livestock	127	137	190	771	961

(R.L. Desjardins, AAFC)

measured CH_4 emission from cattle in their natural setting. They measured the CH_4 concentration in air emitted from vents in a dairy barn and calculated the emission from all cows in the barn, including the manure they produced. Using this approach, they were able to estimate not only the average rate of CH_4 production per animal (about 550 litres per cow per day) but also the daily and seasonal fluctuations in emission rates (Figs. 19 and 20). For example, highest emissions usually occurred immediately after each feeding.
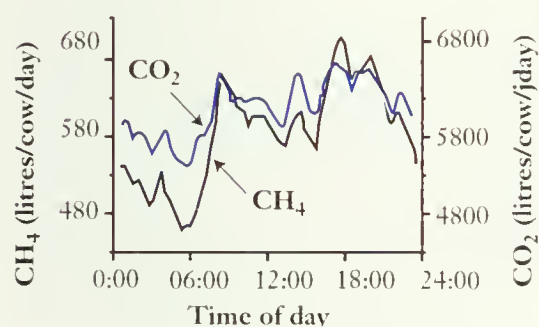
Figure 19

Diurnal pattern of CO_2 and CH_4 emitted by dairy cows. (H. Jackson and R. Kinsman, AAFC)
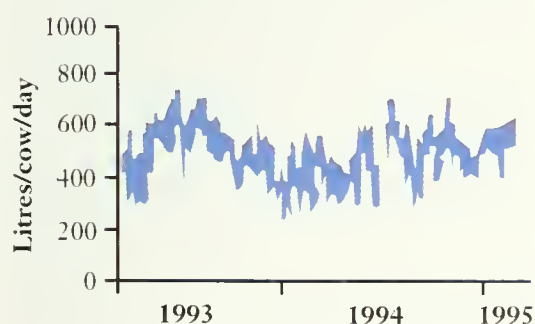
Figure 20

Average monthly emission of CH_4 from a dairy barn in Ottawa. (H. Jackson and R. Kinsman, AAFC)

Emissions from dairy cows

A complete barn, with a handling system for liquid manure, was instrumented to monitor CO_2 and CH_4 emissions from 118 dairy cows and their manure. Experiments such as this help to determine the amount of greenhouse gases emitted from cattle. The rate at which feed energy is converted to CH_4 is based on the quantity and quality of feed. Dairy cows emit much more CH_4 per year than other cattle.

Cows unknowingly participating in an experiment to measure greenhouse gas at the Central Experimental Farm in Ottawa, Ont.

(H. Jackson and R. Kinsman, AAFC)

Measuring CH_4 from cattle on pastures poses more difficult problems. But researchers now have a new technique, based on the use of a chemical marker, to measure directly CH_4 emission from grazing animals. This method, used in a grazing study in Manitoba, showed that emission rates were about 0.7 litre per kilogram body weight per day (0.5 g CH_4 per kilogram body weight per day).

Factors affecting methane emission

Many factors influence the rate of CH_4 emission from ruminants. They are reasonably well known because CH_4 loss represents incomplete use of

feed energy. As much as 15% of the gross energy in feed may be lost through CH_4 emission. As a result, researchers studied the factors affecting CH_4 emission long before the environmental concerns about CH_4 became prominent.

One important factor affecting the rate of CH_4 emission is the quality of the feed. In general, diets that increase the rate of digestion reduce CH_4 emissions, because the feed does not stay in the rumen as long. Thus, several characteristics of the feed can affect CH_4 emission: the amount of roughage in the diet, preservation method, growth stage of forage plant, degree of chopping or grinding, the amount of grain in the diet, and the addition of oils. For example, CH_4 emission may be lower from legume rather than grass forage, from ensiled rather than dried feeds, and from highly concentrated rather than high-roughage diets.

Another important factor is the amount of feed intake. When intake of feed is increased above maintenance levels, the amount of CH_4 emitted per animal increases, but the efficiency of feed usage also increases. Consequently, CH_4 emission per unit of product (e.g., milk or beef) is usually reduced at higher levels of feed intake. For this reason, it is often better to assess CH_4 emission per unit of product rather than per animal or unit of feed.

For animals on pasture, the CH_4 production may be affected by the grazing regime. In a Manitoba study, halving the number of beef cattle per hectare increased CH_4 emission per animal but reduced the emission per hectare. Overall, CH_4 emission per kilogram of weight gain (about 150 g CH_4 per kilogram of gain) was unaffected by grazing practice.

The animal itself—its breed, weight, rate of growth, and whether it is producing milk—affects CH_4 emission. The environment may also affect CH_4 emission. For example, some research suggests that emissions may increase at lower temperatures. Because of the large number of factors that influence CH_4 release from livestock, it may be possible to reduce emissions by changing management practices.

Direct emission of CH_4 from Canadian farm animals can be estimated by multiplying the number of animals by an average emission rate per animal. In 1991, direct emission of CH_4 from Canadian farm animals was about 771 Gg (thousand tonnes) (*see* Table 9). Of this, beef cattle accounted for 72% and dairy cattle for 25%. By comparison, direct emissions from other livestock were almost negligible.

Emission of methane from manure

Methane is emitted not only from the animals themselves but also from the C they excrete (*see* Fig. 18). Manure, like other organic materials, is decomposed by microorganisms. If the decomposition occurs under well-aerated conditions, most of the C is released as CO_2. When oxygen is deficient, however, a lot of CH_4 may be produced instead.

The ratio of CO_2 to CH_4 produced depends on how the manure is managed. Much of the CH_4 from manure is produced during storage. When manure is stockpiled, inadequate aeration inside the pile may lead to CH_4 production. Even higher amounts of CH_4 may be released from manure stored in liquid form because of limited aeration. Thus pig manure, commonly stored as a slurry, may emit high amounts of CH_4. Once manure is applied to the land, it produces little additional CH_4 because of adequate exposure to air.

Using estimates of manure produced and CH_4 emission rates, it is possible to estimate the amount of CH_4 emitted from manure in Canada (*see* Table 9). According to this calculation, emission from manure accounts for about 20% of the total CH_4 emitted by livestock (manure + direct emission). In particular, these estimates point to pig manure as an important source of CH_4, both because of large numbers of animals and because of the way the manure is stored.

Methane emission and absorption by soils

Soils can either release CH_4 or absorb it, depending largely on moisture content. When organic materials decompose in submerged or water-laden soils, the water reduces the oxygen supply causing the release of large amounts of CH_4. Globally, for example, rice paddies are an important source of atmospheric CH_4. In the agricultural soils of Canada, however, CH_4 emission is probably confined to localized wetland areas and perhaps to brief periods when low-lying soils are submerged during snowmelt or after high precipitation. Most soils have enough aeration that they do not produce CH_4; in fact, microorganisms in the soils convert CH_4 to CO_2 so that the soils "absorb" CH_4. The amount absorbed depends to some extent on management practices. For example, CH_4 absorption is usually higher under grassland than in tilled soils and is suppressed by applying N fertilizers.

Although CH_4 absorption by soils is an important mechanism in the global CH_4 cycle, the amounts absorbed by Canadian agricultural soils are probably small compared to total

emissions from farms (Table 10). Researchers estimate net absorption of CH_4 by agricultural soils in Canada to be about 12 Gg (thousand tonnes) per year. Even large increases in amount of CH_4 absorption by soils would offset only a small proportion of current emissions from livestock and manure.

Other sources of methane

Fossil fuels used in agriculture release small amounts of CH_4 by volatilization and combustion. This emission amounts to about 1 Gg (thousand tonnes) of CH_4 per year (see Table 10). Some CH_4 is emitted from the burning of crop residues, but amounts are small and will diminish further because this practice is becoming obsolete.

Estimates of net emission from all sources

Virtually all the CH_4 emission on Canadian farms is from livestock (see Table 10). According to current estimates, about 1 Tg (million tonnes) of CH_4 was emitted from Canadian farms in 1996. Of this amount, about 80% came directly from livestock, the remainder from livestock manure.

Changes in emissions from year to year reflect differences in livestock numbers, which fluctuate depending on costs of feeds, market prices for the products, and export markets. If livestock numbers increase as expected, CH_4 emissions may further increase unless farmers adopt new methods that reduce emissions per animal.

Nitrous oxide

Nitrous oxide is familiar to us as an anesthetic. It occurs naturally in the atmosphere at very low concentrations (about 0.3 ppmv), but the concentration is now increasing at a rate of about 0.3% per year. Much of this increase comes from agriculture, which accounts for up to 70% of the N_2O emissions from human activity.

The increase poses two potential threats. First, N_2O is a potent greenhouse gas with a long lifetime in the atmosphere (about 120 years). Its warming potential is about 310 times that of CO_2 over 100 years. Second, N_2O released is eventually converted in the upper atmosphere to nitric oxide (NO), a gas that breaks down O_3. Ozone in the upper atmosphere filters out UV radiation from the sun, so its depletion results in higher doses of harmful UV radiation reaching the

Table 10 Estimated total CH_4 emissions

	1981	1986	1991	1996
Livestock	849	748	771	879
Manure	208	192	190	208
Soils	-12	-12	-12	-12
Fuels	1	1	1	1
Total (Gg CH_4)	1046	929	951	1076
Total (Tg CO_2 equivalents)	22	20	20	23

(R.L. Desjardins, AAFC)

earth's surface. Higher N_2O levels, therefore, not only contribute to the greenhouse effect but may also increase indirectly the intensity of UV radiation.

Most N_2O from agriculture is produced in the soil. To understand the origins of the N_2O and the factors that affect its emission, it is helpful to review the overall N cycle on farms.

Nitrogen cycle

In terrestrial ecosystems, there are three main pools of N—soil, plants, and atmosphere (Fig. 21). The largest of these is the atmosphere; in the column of air above a hectare of land there are about 76 million kg of N, roughly a million times the amount that plants on that hectare use in a year. Virtually all this N, however, occurs as N_2, a gas that is almost inert and not directly available to plants.
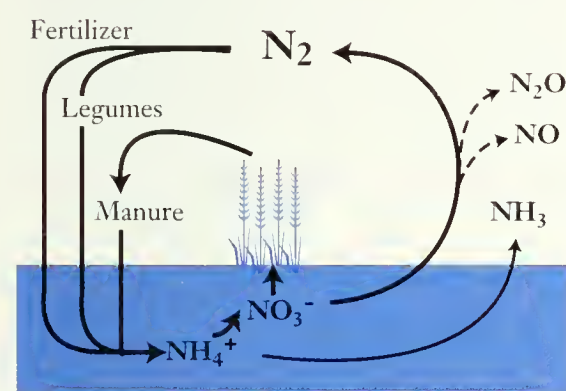
Figure 21

Conceptual N cycle in an agroecosystem.

Despite living in a sea of gaseous N, plants obtain most of the N they need through their roots, by absorbing nitrate (NO_3^-) and ammonium (NH_4^+) dissolved in soil water. When the plants later die, the N in the plant litter is returned to the soil, where it becomes part of the soil organic matter. Soil microorganisms, in turn, gradually decompose this organic matter, releasing NH_4^+, which may be further converted to NO_3^-. These forms are then available again for plant uptake, completing the cycle. In "natural" systems, this cycle between soil and plants can continue almost indefinitely, with only very small inputs of N from the air via lightning or specialized soil bacteria.

In farmlands the N cycle is more complicated, as grain and other products remove large amounts of N from the field. In fact, cropping systems are often designed specifically to maximize the amount of N (as protein) in the plant parts that farmers harvest and remove. In high-yielding wheat, for example, harvesting the grain removes more than 100 kg N per hectare from the field every year. Consequently, to continue the cycle and to maintain crop growth, inputs from outside must replace the lost N.

The main source of new N is the air. There are two ways of converting the otherwise inert N_2 into a form available to plants. One is the industrial approach, which uses energy from fossil fuel to convert N_2 into "chemical" fertilizer. The other is a biological approach, which uses legumes such as alfalfa, clover, beans, and peas to "fix" N_2. These crops have nodules on their roots, containing bacteria that convert N_2 into plant-available form. The plants absorb this N and, when they die and decompose, release it back into the soil as NH_4^+.

The N from fertilizers and legumes has allowed large increases in food production, but, if they are to feed the growing population, producers will

need even larger amounts of N. Already, the global additions of N from these sources exceed inputs from "natural" sources (mainly fixation by lightning and bacteria not associated with agricultural crops). Although this injection of N sustains food production, it exerts pressure on the N cycle and often results in losses or "leaks" of N into the environment (*see* Fig. 21). Large portions of applied N—as much as 50% in extreme cases—may leach into the groundwater. As well, N enters the air in various gaseous forms: ammonia (NH_3), nitric oxide (NO), N_2, and N_2O. Most of these "leaks" occur from the pool of plant-available N (NH_4^+, NO_3^-). Consequently, losses are highest when producers add these forms in amounts greater than the plants can use or at a time when plants are not growing.

Nitrous oxide formation

Nitrous oxide can originate from two places in the N cycle: during nitrification (converting NH_4^+ to NO_3^-), and during denitrification (converting NO_3^- to gaseous N_2). Both processes are carried out by bacteria living in the soil.

Nitrification

Most N enters the soil either as NH_4^+ or in a form that converts to NH_4^+. For example, the N in crop residues occurs largely in organic forms (like protein) which, when decomposed, release NH_4^+. Similarly, most of the N fertilizers used in Canada contain N as NH_4^+, or in a form (like urea), which converts to NH_4^+ soon after application. Most of the N applied to soil, therefore, passes through the nitrification process.

During nitrification, most of the N is released as nitrate (NO_3^-), but a small proportion of the N (usually less than 1%) may be emitted as N_2O (Table 11):

Table 11   Estimates of proportion of N released as N_2O from various fertilizers as estimated in laboratory studies

Synthetic fertilizer	Amount of N fertilizer evolved as N_2O (%)
Urea	0.3
Ammonium sulfate ((NH_4)$_2SO_4$)	0.1
Ammonium nitrate (NH_4NO_3)	0.3
Anhydrous ammonia	1.6
Nitrogen solution	0.3
Calcium nitrate (Ca(NO_3)$_2$)	0.2

(Adapted from a review by E.G. Beauchamp and G.W. Thurtell, University of Guelph)

Organic N

Fertilizer $\longrightarrow$ NH_4^+ $\longrightarrow$ NO_3^-, with N_2O

In general, the more NH_4^+ applied, the more nitrification occurs, and the greater is the potential for N_2O release. But the proportion of N released as N_2O is not fixed; under conditions of good aeration and high NH_4^+, for example, less of the N will appear as N_2O than when oxygen or NH_4^+ concentrations are low. As a result, the amount of N_2O released from nitrification may not correspond

directly to the amount of N entering the process.

Denitrification

When movement of oxygen into soil is restricted, nitrate (NO_3^-) can be converted into nitrogen gas (N_2) in the process called denitrification. Deprived of oxygen in air, some bacteria use NO_3^- instead, thereby releasing N_2. As for nitrification, however, a small proportion of the denitrified NO_3^- may be released as N_2O:

$$NO_3^- \xrightarrow{\qquad \overset{\textstyle N_2O}{\blacktriangledown} \qquad} N_2$$

Three main factors control the rate of denitrification: the supply of oxygen, the concentration of NO_3^-, and the amount of available C (used by bacteria as an energy source). Highest rates of denitrification occur when all three factors are present: low oxygen, high NO_3^-, and high available C. The absence of any one of these three may reduce denitrification to negligible rates. Because it occurs only in the absence of oxygen, denitrification is most intense in water-logged soils. Some denitrification may also occur inside the root nodules of legumes.

The amount of N_2O release, however, depends not only on the rate of denitrification but also on the ratio of N_2O to N_2 produced. This ratio is highly variable and tends to be lower under conditions favoring high rates of denitrification.

Often, we think only of the denitrification that occurs on farm fields. But N that is lost from the soil may also convert to N_2 or N_2O. For example, the NO_3^- that leaches from the soil eventually finds its way into the groundwater or into sediments of streams and lakes. Once there it can undergo denitrification. Consequently, the amount of N_2O produced from farm practices may be much higher than that which is emitted directly from the soil.

Of the two processes, denitrification is probably more important than nitrification as a source of N_2O in Canadian farms. Emissions of N_2O from denitrification may be several times higher than those from nitrification, but it is difficult to distinguish between the two sources, and their relative importance varies widely from place to place.

Management practices affecting nitrous oxide emission

Because of larger N inputs and disrupted N cycling, agricultural soils often have higher rates of N_2O emission than comparable soils under "natural" vegetation. For example, a fertilized barley field near Quebec City had N_2O emissions as high as 7 kg N per hectare per year, compared to negligible amounts (0.04 kg N per hectare) in a nearby forest soil. But the rate of N_2O emission is highly sensitive to conditions in the soil; under many conditions there may be no emission; in others there may be large bursts of N_2O. By their effects on soil conditions, therefore, farming practices can greatly affect N_2O emission.

Form of fertilizer applied

In Canada, producers use a variety of commercial fertilizers to supplement soil N (*see* Table 11). Of these, urea and anhydrous ammonia (pressurized ammonia gas) are the most common, together accounting for almost 75% of the N applied. Most forms include N either as NH_4^+ or in a form that quickly changes to NH_4^+ after application. For example, anhydrous ammonia becomes NH_4^+ immediately upon reacting with water in the soil, and urea is converted by soil enzymes to NH_4^+ and CO_2 within days of being applied. As a result, most of the N in fertilizers passes through the nitrification process (conversion to NO_3^-) with the potential for some to be lost as N_2O.

During their initial reactions, fertilizers may affect pH, soluble C content, and other properties of soil in their immediate vicinity. These effects vary with fertilizer form so that N_2O formation during nitrification may vary among fertilizers. Indeed, some research suggests that there may be large differences in N_2O emission among fertilizer forms. Highest emissions may occur from anhydrous ammonia, and lowest from calcium nitrate, presumably because the N in the latter does not undergo nitrification.

Nitrous oxide emissions from various fertilizer formulations were compared in a study at Elora, Ont. Equivalent amounts of N were applied to turfgrass in one of several forms: ammonium nitrate (NH_4NO_3), urea ($CO(NH_2)^2$), and slow-release urea. There was little N_2O emission from the slow-release urea, probably because its gradual N release coincided with plant N uptake, preventing the accumulation of NH_4^+ or NO_3^-. The other two sources showed significant N_2O emission, with slightly higher values from ammonium nitrate than from urea.

The physical form and placement of fertilizers may also influence N_2O emissions. For example, results of a laboratory study suggest that emissions may be higher from large granules than from fine particles mixed into the soil. The finer fertilizer is more widely dispersed in the soil and, presumably,

Fertilizer consumption in Canada

From 1930 to 1960, the world production of nitrogen, phosphate, and potash was about equal. Since 1960, the use of all three nutrients has greatly increased but that of nitrogen fertilizers has increased faster than that of phosphate and potash. Canada uses about 2% of the world fertilizers.

Much like the global trend, there has been a large increase in fertilizer use in Canada since the 1960s. Most of this increase is in nitrogen fertilizer and occurred in the Prairies. In eastern Canada, fertilizer usage has stabilized or even decreased in the last decade. Compared to other developed countries, Canada has a low rate of fertilizer use per hectare.

Fertilizer consumption in Canada from 1966 to 1996
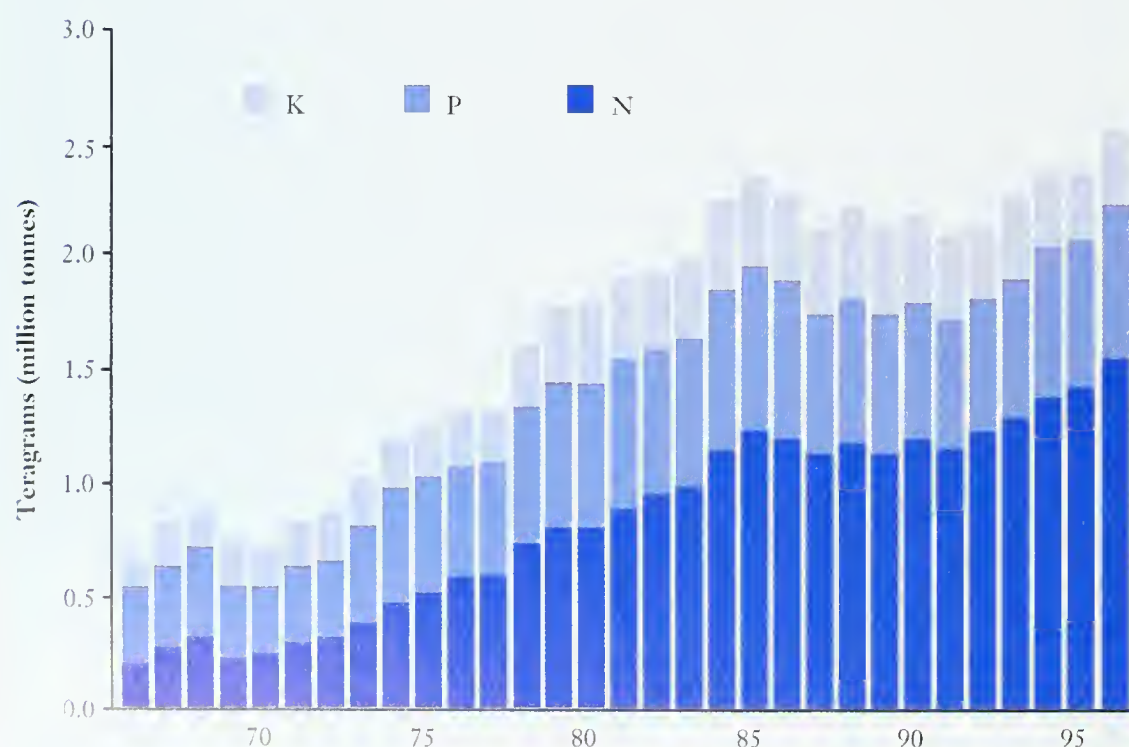
Selecting the fertilizer

Selecting a fertilizer is a question of convenience and cost.
Convenience factors include the following:
- concentration of nutrient
- machinery, training, and maintenance requirements
- safety
- ease of transportation and application
- secondary effect on soil acidity
- possibility of combining with other operations (irrigation, spraying, seeding).

Economic factors include the following:
- cost relative to other formulations
- value of the crop
- efficiency of use by crop.

Nitrogen requirements of crops

Nitrogen is the nutrient needed most to ensure growth of nonleguminous crops, such as corn or wheat. Although leguminous crops, such as alfalfa and soybeans, derive some nitrogen from the soil, most comes from biological fixation. Other sources of nitrogen include synthetic fertilizers and manure. Residues of alfalfa following ploughing or chemical burndown may also supply the succeeding crop with significant quantities of nitrogen.

The optimum rate of application for fertilizer or manure depends on the crop's need for added nitrogen, the anticipated yield, and the availability of nitrogen from previous manure application or leguminous crop residue. Soils differ significantly in their ability to furnish nitrogen to crops. Although data on historical response to nitrogen are generally used to predict the amount of nitrogen required, soil tests can also be used.

Yields of nonleguminous crops may be increased by as much as 50% by adding manure or nitrogen fertilizer. But the amount should not exceed that which will return the most profit. Maximum profit usually occurs at about 95% of maximum yield. When applied at the rate for maximum profit, the nitrogen will be used efficiently, yet as economically as possible.

(E. Beauchamp, University of Guelph, Guelph, Ont.)

Nitrous oxide emissions measured at Elora (using a tower-based flux-measuring system) from a corn field. Bursts of N_2O emissions occur just after spring thaw and following fertilizer application.
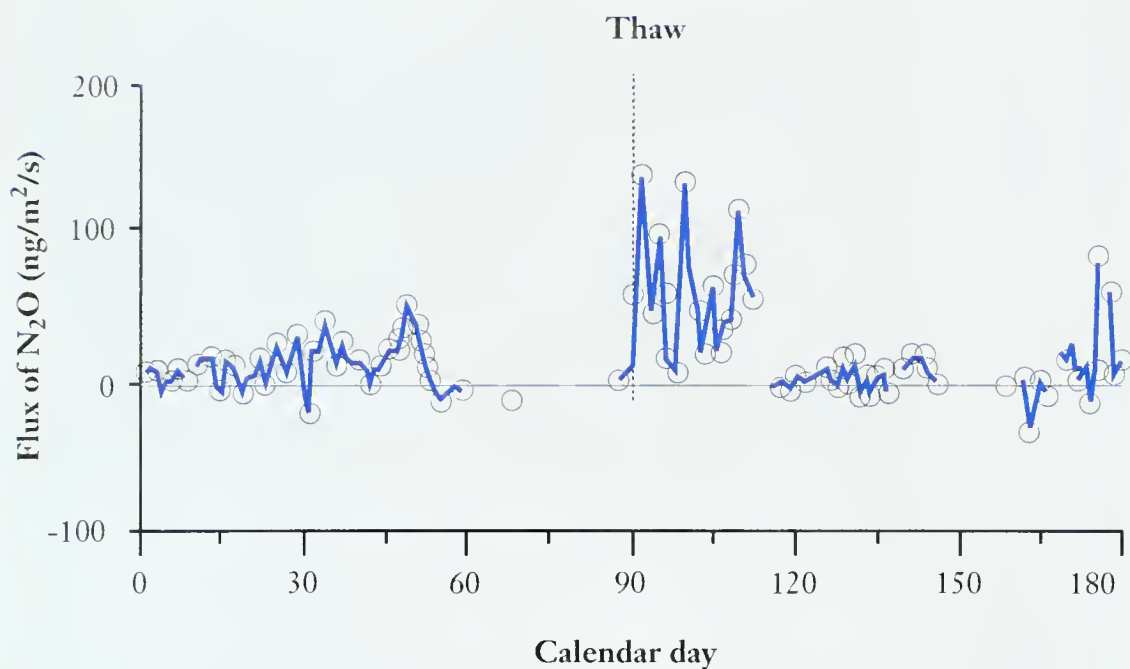
(C. Wagner-Riddle and G. Thurtell, University of Guelph, Guelph, Ont.)

Manure management

Of the N consumed by livestock in feed, as much as 78% is excreted in urine and feces. In 1 year, for example, a dairy cow may excrete as much as 100 kg N or more. Consequently, animal manure contains large amounts of N; in Canada, the N excreted each year by livestock may approach the amount of N applied as fertilizer.

Some N in manures is lost to the atmosphere as NH_3, either immediately or during storage, but most is returned to the land. The N content of manures varies depending on animal, rations, and bedding material but is typically about 2% of dry weight. This N occurs largely in two forms: NH_4^+ and organic N. The former is immediately available to plants and behaves in the soil like NH_4^+ from fertilizer. The organic N, however, acts more like a slow-release form, gradually being converted to NH_4^+ by the action of soil microorganisms.

The N applied in manure is susceptible to loss as N_2O. Because a large part of the N occurs as NH_4^+, some N_2O may be formed during nitrification to NO_3^-. Denitrification may produce much higher amounts, because manure is a source not only of N but also of available C. Applying high concentrations of N and available C together favors denitrification. In extreme cases, where soils have received excessive rates of manure for many years in succession, N_2O emissions may be as high as 50 kg N per hectare per year, though emissions are usually much lower.

The amount of N_2O emitted from manured soils depends on method and rate of application, type of manure, and

has less effect on the pH immediately next to individual particles. Banding fertilizer, similarly, concentrates the N in localized areas and may therefore also affect N_2O emission.

Although these and other data suggest that how a fertilizer is formulated and where it is placed may affect N_2O emission, this effect has not yet been fully defined. Because N_2O emissions also depend on other factors such as rate of application, soil properties, timing of precipitation, and crop rotation, the effect of fertilizer formulation may not always be the same.

soil properties. One study suggests that liquid manure applied in bands may produce more N_2O than manure applied uniformly on the soil surface. Placing the manure in bands concentrates the N and C, creating conditions more favorable for denitrification.

Manure management may also have indirect effects on N_2O emission. A large portion of N excreted from livestock, as much as 50%, may be released into the atmosphere as ammonia (NH_3) gas. This NH_3 is eventually deposited onto soil or water, where it reverts to NH_4^+ and can be lost as N_2O like N applied directly.

Crop residue input and soil management

Crop residues (e.g., straw, roots) and other plant materials return much N annually to the soil. In many cases, this N is merely a recycling of N absorbed earlier from the soil. But legumes, which can capture N_2 from the air, can actually add new N to the soil. Sometimes crops grown solely for the purpose of capturing N are ploughed back into the soil as "green manures."

The amount of N_2O produced from added plant materials depends on the rate of N release. Some residues, such as wheat straw and corn stover, have a low N concentration, commonly less than 0.5%. When these materials decompose, they release little N; in fact, sometimes they even result in the withdrawal of NH_4^+ or NO_3^- from the soil because the microbes need extra N to decompose the residue. In contrast, N-rich materials such as legume residues or green manures can quickly release large amounts of NH_4^+ (later converted to NO_3^-) during

decomposition. Like animal manure, these materials also provide a ready source of available C, favoring the release of N_2O from denitrification. For example, alfalfa residues may release 2–4 kg N_2O-N per hectare and soybean residues 0.3–2 kg N_2O-N per hectare per year.

The way in which farmers manage crop residues may also influence N_2O emission. Tillage may be the most important tool for managing residues. Normally, tillage mixes crop residues into the soil, but in no-till or other "minimum tillage" systems the residues remain on the soil, altering decomposition patterns. Some studies suggest that no-till techniques may

Injecting liquid manure

Injecting liquid manure into the soil prevents rapid loss of nitrogen compounds into the air and minimizes release of unpleasant odors. If the soil is loosened-up at the same time, deep soil fissures will be broken, and the liquid will not drain directly into the drainage tiles. Because manure tankers are very heavy and will compact moist soil, such as occurs in early spring, it is often difficult to find appropriate times to apply liquid manure.

Table 12 Comparison of N_2O emissions in central Alberta as affected by tillage

	1993–94	1994–95
	N (kg/ha)	
Till / with fertilizer	1.7	2.5
Till / no fertilizer	0.6	2.4
No-till / with fertilizer	1.7	0.9
No-till / no fertilizer	0.6	0.4

(R. Lemke, University of Alberta)

increase N_2O emission; others conclude that no-till can reduce emissions (Table 12). How tillage affects N_2O emission, it seems, depends on soil, cropping system, climate, and other factors. Aside from their effect on residue placement, tillage practices also influence soil moisture, temperature, and aeration, all of which affect N_2O production.

Soils, even without recent additions of residues or other N, can emit N_2O from their decomposing organic matter. Organic soils, because of their rich organic N reserves, may release particularly high amounts of N_2O— about 5 kg N per hectare per year. Similarly, soils that are left unplanted for a year (a practice known as summer fallow) may emit significant amounts of N_2O. Soil microbes gradually break down the organic N in these soils into NH_4^+ and NO_3^-, and because there are no growing plants to remove this N, it accumulates and is highly susceptible to loss via denitrification.

Amount and timing of nitrogen application

Often, N_2O emission is assumed to be directly proportional to the amount of N applied. But a better measure may be the amount unused by the crop. Matching the NH_4^+ or NO_3^- released into the soil precisely to their uptake by plants prevents these N forms from accumulating in the soil, and N_2O losses will be minimal. Such ideal synchrony, however, rarely occurs. Often NH_4^+, and particularly NO_3^-, accumulate in excess of the plants' capacity to absorb them, resulting in high potential for N loss via leaching or denitrification. This situation is especially true if the NO_3^- accumulates after harvest, because then it is vulnerable over the fall, winter, and, especially, the following spring, when denitrification is particularly intense. Consequently, matching the amount and time of N application with plant N uptake pattern is an important management tool to minimize N_2O emissions.

Nature of nitrous oxide emission

Nitrous oxide emissions are usually sporadic. Unlike CO_2, which is released from soil almost continuously, N_2O is often emitted in bursts or "flushes." Under Canadian conditions, the most important of these flushes may occur in early spring, as the snow melts. At a site in central Alberta, for example, most of the N_2O emitted in the entire year occurred during 10 days at the end of March (Fig. 22). These bursts of N_2O emission at snowmelt may reflect favorable conditions for denitrification and N_2O formation: high moisture content

(oxygen deficiency), adequate NO_3^- and available C, and favorable temperature. Or the N_2O flush may reflect the abrupt release of N_2O that was previously trapped under a layer of frozen soil or ice. Although the spring flush is often the largest, additional bursts of N_2O follow heavy rains that result in water-logging of soils, especially in low-lying areas. As well, N_2O may erupt immediately after fertilizer is applied because of the sudden availability of N.

Emission of N_2O is sporadic not only over time but also across space. This variability stems, in part, from the differences in N and moisture (hence oxygen) content across the landscape. At any time, there may be minimal release of N_2O from most areas in a field, but high emissions from small "hot spots" where conditions are ideal for N_2O production.
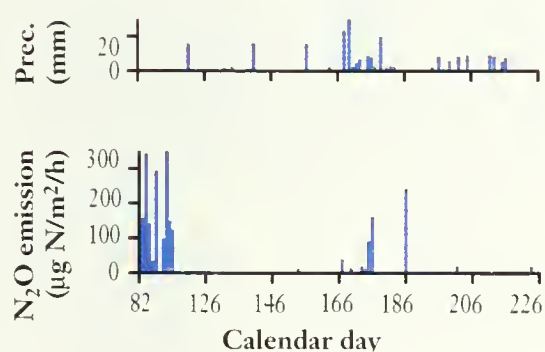
Figure 22

Seasonal pattern of precipitation and N_2O emissions from a fertilized wheat field at Ellerslie, Alta., 1993. (R. Lemke, University of Alberta)

A further complication is that much of the N_2O is often produced in deeper soil layers. The release of this N

Nitrous oxide emissions in the winter

Eastern Canada, where soils can be covered with snow for up to 5 months, has a relatively short growing season. We once thought that N_2O emissions during winter were minor and of little importance in the annual N-budget. But we now know that significant losses of nitrogen as N_2O occur from under the snow cover. In certain cases, soils release substantial amounts of N_2O during the winter. Freeze–thaw cycles also affect the N_2O emissions from soils. These cycles induce physical and biological changes to the soil; they disrupt soil structure and stimulate denitrification leading to more N_2O production.

(E. van Bochove, AAFC)

depends on its rate of diffusion to the soil surface, which is controlled by soil porosity and the presence of ice or water at the surface. The trapped N_2O may also be dissolved in soil water or be further converted to N_2 or to NO_3^- by microbes, so that the N_2O formed at depth is not all released to the atmosphere. Consequently, N_2O emission from soils depends not only on how fast it forms but also on how fast it diffuses or converts to other N forms.

Until recently, we thought little N_2O would form over winter because of low

soil temperatures. But this idea may not hold true where snow insulates the soil. In parts of eastern Canada, for example, snow blankets the soil thickly for up to 5 months per year, keeping soil temperature above or near freezing. As a result, N_2O can be produced all winter and be released through the porous snow. At a site near Quebec City, a fertilized barley field, ploughed the previous fall, released up to 5 kg N per hectare during the winter and spring, equivalent to 5–10% of the fertilizer N applied. The same field released only 2 kg N during the growing season.

Because of the sporadic and unpredictable pattern of N_2O release, estimating amounts of emission is difficult. Hence, current estimates of N_2O emission are probably less reliable than those for the other greenhouse gases.

Estimates of national nitrous oxide emission

Given our limited understanding of N_2O formation and release, we can estimate only tentatively N_2O emissions from Canadian farms. Current estimates rely on simple equations, developed by the International Panel on Climate Change (IPCC), that calculate N_2O release from three sources: direct emissions from soils, direct emissions from livestock production, and indirect emissions from farms.

Direct emissions from soils include N_2O derived from fertilizer, land-applied manure, legumes, and crop residues. Researchers calculated emissions from the total N content of these sources, based on national statistics, assuming that a specified proportion of the N was released as N_2O (about 1%, depending on source). They also included estimates of N_2O release from organic soils, though these amounts are small. Based on this calculation, they estimated direct emissions of N_2O from agricultural soils in Canada in 1996 to be 70 Gg (thousand tonnes) of N_2O (Table 13). When averaged over the area of cultivated land in Canada, this amount equates to about 1 kg N per hectare per year. The estimated emission rates, however, vary widely among regions (Fig. 23 a,b).

The scientists calculated direct emissions from livestock by estimating the amount of N in manure and assuming that a specified portion of that N was emitted as N_2O. They assumed the fraction of N converted to N_2O to

Table 13 Estimates of direct and indirect sources of N_2O emissions from Canadian agriculture in 1996

Province	Direct emissions from soils	Direct emissions from manure	Indirect emissions	Total N_2O emissions
		(Gg N_2O)		
Atlantic	0.9	0.5	1.0	2.4
Quebec	5.7	2.4	4.0	12.1
Ontario	13.1	3.7	6.0	22.8
Manitoba	10.6	2.3	5.7	18.6
Sask.	19.1	4.5	9.2	32.8
Alberta	18.4	9.6	10.8	38.8
B.C.	1.9	1.5	1.5	4.9
Canada	69.7	24.5	38.2	132

(R.L. Desjardins, AAFC)

be 2% for grazed animals and 0.1–2% for other livestock, depending on waste management. Using this approach, they estimated direct emissions from livestock to be 24.5 Gg (thousand tonnes) of N_2O in 1996 (*see* Table 13).

They also calculated indirect emissions from estimates of atmospheric N (e.g., NH_3) deposited on the soil, N leached from farm fields, and N produced from human sewage. According to these calculations, leached N is the most important, accounting for more than 80% of the roughly 38 Gg (thousand tonnes) of N_2O released from indirect sources in 1996 (*see* Table 13). This estimate assumed that 30% of the N applied as fertilizer or manure leached into the groundwater.

Based on the IPCC approach, total emissions of N_2O from agriculture in

Figure 23a

Estimated direct N_2O emissions from agricultural sources in western Canada for 1991.

WESTERN CANADA

Kg N_2O per square kilometre

LEGEND

	0 - 75
	75 - 150
	150 - 225
	225 - 300
	300 - 375
	375 - 450
	450 - 525
	> 525
	Non Applicable
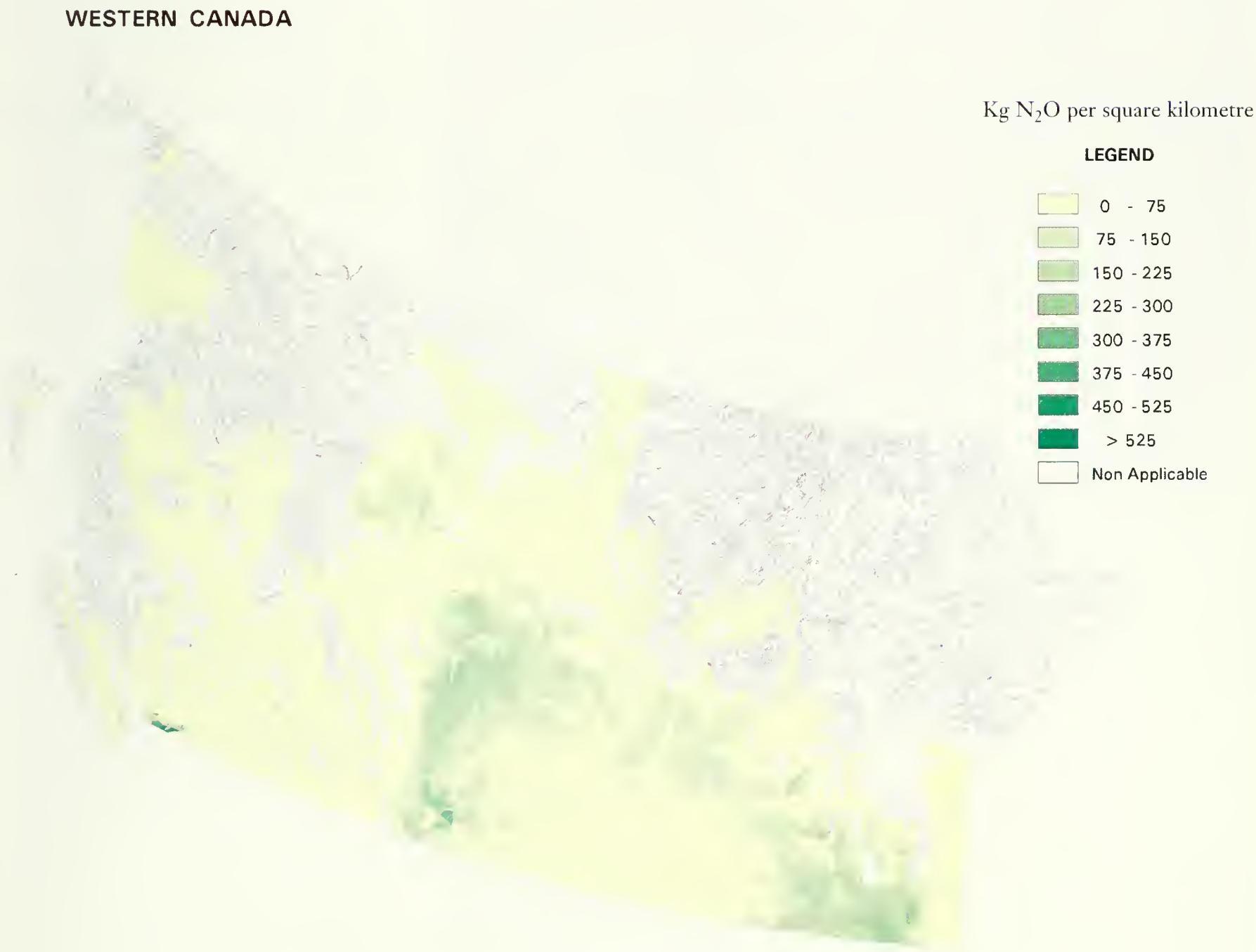
Figure 23b
Estimated direct N_2O emissions from agricultural sources in eastern Canada in 1991.

Kg N_2O per square kilometre

LEGEND

	0 - 75
	75 - 150
	150 - 225
	225 - 300
	300 - 375
	375 - 450
	450 - 525
	> 525
	Non Applicable
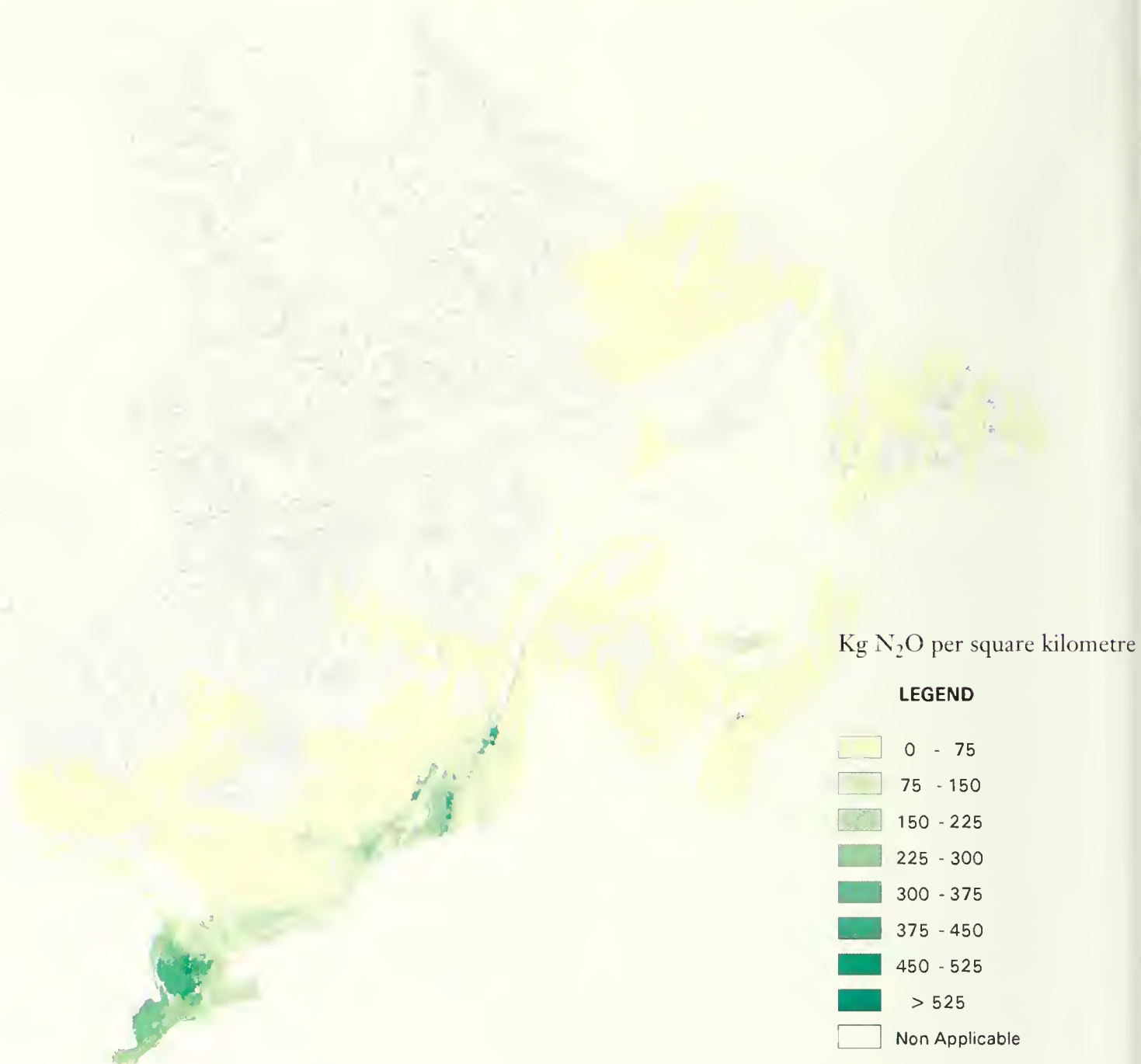
Canada in 1996 were about 132 Gg (thousand tonnes) of N_2O (see Table 13). Of this, direct emissions from soils accounted for about half.

The trend in N_2O emissions over time may be as important as the total amount. Current estimates suggest that N_2O emissions have increased steadily since 1981, increasing by 20% from 1991 to 1996 alone. Much of the increase resulted from higher N inputs as fertilizers and animal manure. With increases in livestock numbers and higher crop yields expected in the future, N_2O emissions may climb still further unless producers make improvements in N management.

Combined effect of the three greenhouse gases

The three gases (CO_2, CH_4, and N_2O) differ in their warming effects. To compare their relative effects, therefore, their emissions are usually expressed as "CO_2 equivalents." One kilogram of N_2O has the warming effect of about 310 kg of CO_2 (when considered over 100 years), so it represents 310 CO_2 equivalents. Similarly, 1 kg of CH_4 represents 21 CO_2 equivalents.

According to best estimates, using the approaches described for each gas, Canadian agriculture had emissions of 67 Tg (million tonnes) of CO_2 equivalents in 1996 (Table 14). Of this amount, about two-thirds was as N_2O and about one-third as CH_4. By comparison, net emissions as CO_2 were almost negligible.

The estimates of CO_2 emission, however, exclude most of the CO_2 from fossil fuels used to produce inputs, power farm machinery, and transport products. These sources, which are included in inventories for transport and manufacturing sectors, emitted about 25 Tg (million tonnes) of CO_2 in 1996.

The emission of greenhouse gases from Canadian agriculture are increasing, according to current estimates (see Table 14). By 2010, emissions may be about 9% higher than those in 1996, unless producers adopt better management practices. These projected increases stem largely from predicted increases in livestock numbers and N inputs as fertilizer and manure. Emissions of CO_2 are expected to decline, but not nearly fast enough to compensate for predicted increases in the other gases.

Future emissions will depend on changes in farming practices that are hard to predict. Livestock numbers, crops that are grown, fertilization patterns, and manure management techniques can all change quickly, throwing off our current best projections.

Global warming potential

Global warming potentials (GWPs) are a simple way to compare the potency of various greenhouse gases. They help policy makers compare the effects of reducing CO_2 emissions relative to another greenhouse gas for a specific time horizon. For example, a small reduction in N_2O can be just as if not more effective than a larger reduction in CO_2 emissions.

The heat-trapping potential of a gas depends not only on its capacity to absorb and re-emit radiation but also on how long the effect lasts. Gas molecules gradually dissociate or react with other atmospheric compounds to form new molecules, with different radiative properties. For example, CH_4 has an average residence time of about 12 years, N_2O 120 years, and CO_2 200 years. Over a 20-year period, CH_4 has 56 times the radiative impact of CO_2. However, as time proceeds some of the CH_4 molecules are broken down into CO_2 and H_2O. Therefore, over a 100-year period, CH_4 has a global warming potential of 21 times that of CO_2.

Global warming potentials are presented for 20-, 100-, and 500-year time horizons. In *The Health of Our Air*, we use the 100-year GWPs recommended by IPCC. Calculations of warming potential are continually refined, so these numbers are subject to revision as understanding improves.

Relative global warming potential
(CO_2 equivalents per unit mass of gas)

Gas	Time horizon		
	20 y	100 y	500 y
CO_2	1	1	1
CH_4	56	21	6.5
N_2O	280	310	170

Agri-environmental indicators

An agri-environmental indicator is a measure of change, or the risk of change, in environmental resources used or affected by agriculture. Although the indicators are national in scope, regional variations are taken into account. Six indicators are being developed, each of which has several components as follows:

Farm resource management:
tracks farmers' use of environmentally sustainable management practices, by measuring soil residue cover and management of agricultural land, fertilizers, pesticides, and manure.

Soil degradation risk:
measures progress in reducing the vulnerability of agricultural soils to degradation and identifies soils still at high risk of erosion, salinization, compaction, or loss of organic matter.

Water contamination risk:
assesses progress in reducing the risk of water contamination by nutrients

used in agriculture and identifies the areas at risk of contamination.

Agroecosystem greenhouse gas balance:
estimates trends in the net emission of CO_2, N_2O, and CH_4.

Agroecosystem biodiversity change:
monitors biodiversity in agricultural ecosystems by measuring changes in habitat availability.

Input use efficiency:
measures the efficiency of fertilizers, energy, and irrigation water used by farmers to track possible effects on the environment.

(T. McRae, AAFC)

Uncertainties in current estimates

Current estimates of greenhouse gas emission are not without uncertainty. We face many possible pitfalls in calculating emissions for ecosystems as extensive and diverse as Canada's farmlands. We still do not even understand all the processes that affect emissions. And so we admit that each estimate is subject to potential error. Of the three gases, N_2O has the highest degree of uncertainty (Fig. 24). Estimates for this gas could be off by 50% or more. Despite their uncertainty, these values are the first comprehensive estimates of greenhouse gas emission from Canadian agriculture and provide a reference point for showing trends.

Though valuable as a first approximation, the estimates will likely change as we learn more. Ongoing research will teach us more about the processes leading to emission and allow

Table 14 Estimates of total greenhouse gas emissions from Canada's agroecosystems

	1981	1986	1991	1996	2000*	2005*	2010*
				(Tg CO_2 equivalents)			
CO_2	9	7	5	3	1	0	0
CH_4	22	20	20	23	23	24	25
N_2O	32	33	34	41	43	45	48
Total	63	60	59	67	67	69	73

* Predicted using a scenario of medium growth from Canadian Regional Agricultural Model (CRAM) to 2007. All 2010 data follow a best-fit trend using data from 1993 to 2007 from the CRAM. All fertilizer data were predicted using a best-fit trend from 1981, 1986, 1991, and 1996 Census data. All sheep, chicken, and turkey populations were predicted using a best-fit trend from Census data.

(R.L. Desjardins, AAFC)

us to build better models. As well, new techniques that simultaneously measure all three gases over large areas will allow us to evaluate better the models' reliability. We can therefore expect more definitive estimates in the future, but we need not wait for their arrival before trying to reduce actual emissions.
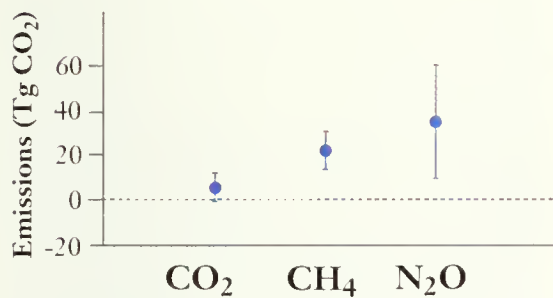
Figure 24

Estimates of CO_2, CH_4, and N_2O emissions in CO_2 equivalents from Canadian agriculture, showing relative uncertainty for each gas.

Techniques to minimize emission of greenhouse gases

Agriculture is a net emitter of greenhouse gases. Furthermore, current predictions point to increased emissions unless some changes are made to farming practices. Fortunately, farmers can adopt several measures to reduce emissions. Some of these would be expensive, but some can be used with little cost or even at higher profit. Widespread use of such practices could reduce emissions of all three greenhouse gases and, for CO_2, even make farms net absorbers.
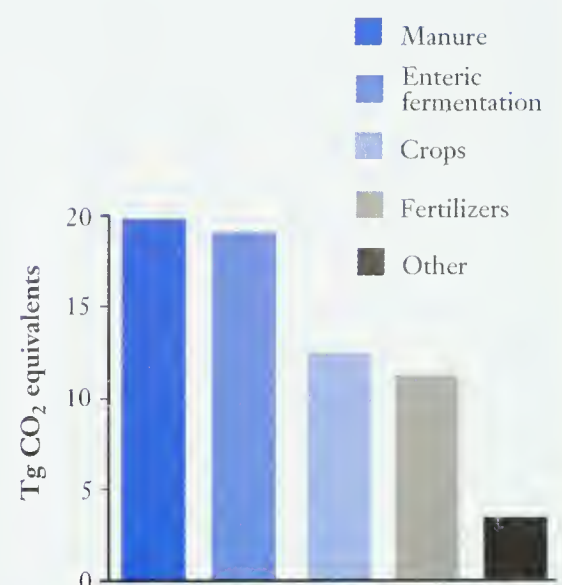
Population of hogs in Canada

Future greenhouse gas emissions depend on economic trend. For example, the Canadian Regional Agricultural Model (CRAM) estimates that, by 2010, the hog population in Canada will be about 14 million. This population is an increase of 36% over that recorded in 1990. This increase may cause N_2O and CH_4 emissions from manure to greatly increase. Hogs produce the second highest amount of manure per 1000 kg of live animal per day, which is equivalent to 10 kg CH_4 per animal per year. Therefore, the CH_4 emissions from hog manure, in 2010, is expected to be about 143 Gg (thousand tonnes) of CH_4, which is 25 Gg higher than 1996 emissions from hogs.

Greenhouse gas emissions from agriculture

Agriculture contributed about 10% of Canadian anthropogenic greenhouse gas emissions in 1996. Using the global warming potentials, the major sources of emissions of all the gases were converted into CO_2 equivalents. From agriculture, the major sources are manure, enteric fermentation, crops, and fertilizers.

- Manure
- Enteric fermentation
- Crops
- Fertilizers
- Other

(R.L. Desjardins, AAFC)

Conservation tillage

Conservation tillage prior to potato planting in Prince Edward Island. Minimum tillage in corn in Ontario and wheat in Saskatchewan.

Reducing carbon dioxide emissions

Farming means managing carbon. On every hectare of farmland, many tonnes (Mg) of C are removed from the air every year and changed to organic materials through photosynthesis (see Figs. 8, 9). At the same time, decomposing organic matter and the burning of fossil fuels releases roughly equivalent amounts of CO_2 back into the air. By their choice of farming practices, farmers can manage this cycle, altering it to reduce net emissions of CO_2.

There are two main ways of reducing emissions: one is to increase the amount of C stored in soil; the other is to burn less fuel. Several practices are already available to achieve each of these.

Increasing soil carbon

In soils that have been managed in the same way for many years, the C content is reasonably constant. A change in management, however, can result in losses or gains of C. To increase soil C, we can do one of two things: increase the amount of C added to the soil, or slow the rate at which soil C is decomposed (decayed) back to CO_2 (see Figs. 8, 9).

Adding organic matter

Atmospheric CO_2 enters the soil by way of photosynthesis. This process traps CO_2 in organic forms, a portion of which is added to the soil as residues (including roots). The only direct way to increase C additions, therefore, is to use practices that favor higher photosynthesis; in other words, practices that increase plant yield.

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Farmers can achieve such increases by using higher yielding crops and varieties, by improving crop nutrition (using fertilizers and manures), or by reducing water stress (by irrigation, water conservation, or drainage). Actions that improve soil quality also promote higher yields. Perhaps most important is to use cropping systems that keep actively growing (and photosynthesizing) plants on the land as long as possible.

But increased photosynthesis helps build soil C only if at least some of the additional trapped C is returned to the soil. The more of the plant removed from the field as grain or other products, the less the increase in soil C. Thus, using cropping practices that keep all residues in the field and planting crops (like forage grasses) that store much of their C in roots can achieve soil C gains. Often, animals help recycle the C back into soil. In many livestock-based systems, a large part of the plant yield is returned to the soil as manure, and only a small portion is actually exported from the field or pasture.

Reducing decay rate

The other way to build soil C is to slow the rate of organic matter decay in the soil. One method of doing that is to make conditions less favorable for soil microbes. For example, residues on the soil surface keep soils cooler, slowing decay. Similarly, maintaining growing plants on the surface as long as possible slows decay, because plants dry out the soil and cool it by shading.

Decay rate can also be slowed by shielding the organic matter from soil microbes. Soils are usually granulated, with organic materials protected inside the granules (or aggregates). Breaking these aggregates open by intensive tillage exposes that organic matter to soil microbes. As a result, practices that minimize soil disturbance tend to preserve soil C.

Another way to shield organic materials is to place them where conditions are not favorable for decay. For example, they can be kept on the surface where they tend to stay dry, or placed deep in the profile, where soil is cool (although this approach would require intensive tillage).

Practices that increase soil carbon

Much can now be done to promote soil C gain, either by adding more C or slowing decay (or both). The following methods are often effective, though the amount of C gain depends on climate and soil type:

Reduce tillage: Tillage was once necessary to control weeds and prepare soil for planting. But now weeds can be controlled with herbicides, and new seeding equipment can place seeds directly into untilled soil. As a result, intensive tillage is no longer necessary, and a growing number of farmers have eliminated tillage entirely, using no-till or "direct-seeding" practices. These practices protect C inside aggregates and keep residues on the surface where they decay more slowly and cool the soil beneath them. No-till and other "reduced tillage" practices also prevent erosion, thereby preserving soil quality and maintaining future photosynthesis. No-till, already used on about 14% of cropland in 1996, could be adopted on a large proportion of Canada's cropland.

Apply more nutrients: Where soils do not have enough nutrients, adding

Trees on agricultural land as a carbon reservoir

Farmers have long planted trees as shelterbelts and for other environmental reasons. Since "afforestation"—the practice of planting trees on previously untreed land—is explicitly recognized as a legitimate carbon offset under the Kyoto protocol, we need to know how much C can be stored in such trees and at what rate.

Prairie Farm Rehabilitation Administration (PFRA) Shelterbelt Centre at Indian Head, Sask., has determined the quantities and rates of C stored in prairie shelterbelts. Typical shelterbelt trees contained from 162 to 544 kg C, with poplar trees having the most. Shrub shelterbelts contained as much as 52 tonnes C per kilometre.

(J. Kort, AAFC)

fertilizers, animal manure, or green manure increases yields, leading to higher inputs of C. Manures may also improve the physical condition or "tilth" of the soil, further increasing yields and residue additions.

Grow more perennial forage crops: Perennial crops can trap more CO_2 than annual crops because they continue growing for more months of the year. Because they dry out the soil more and there is no tillage, decay rates may also be slower. Many perennial crops, like grasses, have extensive root systems that place much C below-ground.

Remove land permanently from cultivation: Probably the most effective way of increasing soil C is to allow the land to revert to its original vegetation, whether grasses or trees. Because there is little or no removal of C in products, virtually all the C trapped by photosynthesis is returned to the soil or stored in the wood. In theory, such "set-aside" lands would eventually regain all the C lost since cultivation began. However, this option means a loss in productivity so it is probably only feasible on marginal lands. The practice may also be applicable in small areas of cultivated land planted to shelterbelts or grassed waterways for control of wind and water erosion.

Eliminate summer fallow: Leaving land unplanted for a growing season (summer fallow) helps control weeds and replenish soil moisture. But it results in soil C loss because, during the fallow year, no new residue is added and the soil remains warm and moist, which hastens decay. A shift to continuous cropping (growing a crop every year) therefore favors increases in soil C. The area of summer fallow has declined in recent years, but it still occupies about 6 million hectares every year. Eliminating summer fallow may not be practical in very dry regions, such as parts of the southern prairies.

Use cover crops: Where the growing season is long enough, a winter cover crop can be sown after the main crop has been harvested. This practice can add more residues to the soil and prevent erosion.

Avoid burning of residues: When residues are burned, almost all their C

is returned to the atmosphere as CO_2, which reduces the amount of C added to the soil.

Use higher yielding crops or varieties: Crops or crop varieties that have more efficient photosynthesis often produce more residues, which increases soil C. But because plant breeders choose varieties based on marketable yield (e.g., grain yield), residue and root yields of new varieties may not increase as much as the yield of harvested product.

Improve water management: Water is often the limiting factor to crop growth. In the dry southern prairies, yields can be increased by irrigating or by trapping and storing water more effectively (e.g., using crop residue or windbreaks to trap snow). In parts of central and eastern Canada, conversley, crop growth may be limited by excess water in poorly drained soils. In these conditions crop growth and C additions to soil can be increased by drainage.

Restore wetlands: Some low-lying areas in farmlands have been drained to allow crops to grow. Re-submerging these soils would cut off oxygen supply, preventing decay. These restored wetlands or "sloughs" could gain a lot of C quickly, though the small area of potential wetlands would limit CO_2 removal.

Integrate livestock into cropping systems: Feeding crops to livestock results in effective recycling of C if the manure is managed well. Thus, although large amounts of C may be removed from the field as forage or silage, much of this C can be eventually returned as manure. The manure also promotes crop growth and photosynthesis, favoring further soil C inputs.

Improve grazing management: The way a grassland is grazed can affect the C cycle in several ways. It influences the proportion of the plant "harvested" by the animal, the redistribution of C in manure, the condition of the soil (via hoof action), and the species composition. Because of these many effects, the relationship between soil C and grazing regime is still unclear. Overgrazing, however, can result in large losses of C via erosion. Reducing the number of animals per hectare on such lands will likely increase the amount of C stored.

Many studies across Canada have shown that these practices can increase soil C. The amount of potential gain, however, is still unclear and will vary depending on the initial soil C content, soil properties, climate, and other factors. The extent to which farmers adopt these practices also influences the amount of C gain. That will depend on crop prices, costs of production, and other factors that fluctuate from year to year.

Despite the uncertainty, some estimates suggest that agricultural soils in Canada could gain as much as several million tonnes of C per year if these C-conserving practices were widely adopted. Such a gain would result in a net removal of CO_2 from the atmosphere. With time, however, the rate of C gain would decline because it becomes harder to add additional C as the C content of soil goes up.

Storing carbon in plant material

Although the soil is the main storehouse of C in farm ecosystems, plant material can store additional C. One way to store more plant C is to grow trees on farmland, either as shelterbelts (which also control erosion) or as woodlots alongside farmsteads. The net benefit of this practice for atmospheric CO_2 depends on the area of land devoted to trees, their rate of growth, and the fate of the wood. If the wood is burned, for example, there is little long-term benefit unless its use reduces dependence on other fuels.

Another way of storing plant C is to convert crop residues into products with a long lifetime. One approach is to construct fiberboard (wood-like panels) from cereal straws. These materials are used for construction and, whereas much of the C in straw returned to soil would normally decay back to CO_2, the C in these construction materials remains trapped for a long time.

Reducing fossil fuel use

Farms rely on energy from fossil fuels to power machinery, heat buildings, dry harvested crops, and transport goods. Energy is also used to supply materials employed on the farm, such as fertilizers, pesticides, machinery, and buildings. Most of these emissions are not attributed to agriculture in the national inventory of greenhouse gases. Even so, using less fuel on farms would reduce Canada's total CO_2 emissions.

The amount of fuel used on the farm and in the supply of farm inputs can be reduced in the following ways:

Reduce tillage: It takes a lot of energy to lift and turn soil during tillage. Reducing or stopping tillage can, therefore, save on fossil fuel use. One Ontario study showed diesel fuel use reduced from 30 litres per hectare for conventional tillage to only 4 litres per hectare in a modified no-till system. A study on the Prairies, which considered both direct and indirect use of fuel, showed that reducing tillage decreased emissions from direct fuel use by about 40% (*see* Fig. 15). Emissions for pesticide inputs were slightly higher under reduced tillage and emissions from fertilizer were unchanged. When all the direct and indirect factors were counted, emissions from no-till were 92% of

Storing carbon in strawboard

Strawboard made from crop residues can store C and may help mitigate greenhouse gas emissions. At the end of their lifetime, the boards could be burned in power plants, replacing fossil fuel, resulting in a true reduction in CO_2 emissions.

One example is the industrial Isobord plant in Elie, Man. It expects to use 180 000 tonnes of wheat straw per year, which is equivalent to sequestering 267 000 tonnes of CO_2 per year. The plant at Elie has already sold 80% of its first 5 years' production.

those in conventional tillage, and emissions from minimum tillage were intermediate.

Use fertilizer more efficiently: Making and transporting fertilizer is energy-intensive. For each kilogram of fertilizer N used, about 1 kg of C is released into the atmosphere as CO_2. Consequently, methods of applying fertilizer that produce high yields from less fertilizer can reduce CO_2 emissions. Possible approaches include placing fertilizer more effectively (e.g., banding); applying only as much as is needed, based on soil tests; and using variable rates of application on a field to reflect differences in soil fertility ("precision farming").

Grow legumes: Legumes can often get much of the N they need from the air. When they die and decompose, they also release N into the soil. Careful use of legumes in cropping systems, therefore, can reduce the amount of N fertilizer needed, and thereby lower CO_2 emissions. For example, in a study at Melfort, Sask., introducing pea into the crop rotation reduced CO_2 emissions from fossil fuel by about 28% (Table 15).

Use manure more efficiently: Animal manure contains many nutrients. These nutrients, however, are not always used efficiently, in part because of the high cost of transporting the heavy, bulky manures. Avoiding excessive application rates of manure in localized areas would not only prevent harmful loss of nutrients to the environment but also save on fertilizer use, thereby reducing CO_2 emissions.

Increase energy use efficiency: Additional opportunities for reducing energy use include drying crops in the field

Table 15 Impact of planting a legume on C emissions in a Saskatchewan cropping system

Rotation (legume or no legume)	CO_2 emissions (kg C/ha/y)
Pea–Barley–Wheat	82
Barley–Barley–Wheat	114

(E. Coxworth, Saskatoon, Sask.)

wherever possible, using more efficient irrigation systems, and insulating farm buildings. As well, many of the energy conservation measures advocated for urban areas also apply to the farm.

An entirely different way of reducing emissions from fossil fuels is to grow crops that provide an alternate energy source. This "biofuel" can displace fossil use, thereby indirectly reducing CO_2 emission. Instead of extracting C from deep within the earth and burning it to CO_2, biofuel production simply recycles the C originally removed from the atmosphere by photosynthesis.

The most efficient way of using crop materials for fuel is to burn them directly. Although this approach is used in some parts of the world, it is not always practical in Canada, where the fuel may have to be transported great distances.

An alternative is to ferment crops, producing ethanol and mixing it, at proportions of about 10%, with gasoline. This mixture can be used in most gasoline engines and reduces the amount of CO_2 produced from fossil fuel. The net savings in fossil fuel use,

Ethanol as a fuel

In 1997, Canadians used about 40 million litres of ethanol and 34 billion litres of gasoline, so ethanol represents about 0.1% of total gasoline sales in Canada. Ethanol has a lower energy content than gasoline. But when carefully blended at less than 10%, mileage is not affected.

Ethanol is a liquid alcohol produced by fermenting either starch materials (corn, wheat, barley) or cellulosics (agricultural residues, wood, wood wastes). Much of the CO_2 released when biomass is converted to ethanol and burned in car engines is recaptured when new vegetation is grown, thus offsetting the greenhouse gas effect. Net lifecycle CO_2 emissions from burning 10% ethanol-blended gasoline have shown about 3% reduction when compared to regular unleaded gasoline. Recent developments in the ethanol industry are expected to increase Canadian production from wheat and corn to about 350 million litres by 2000.

(M. Stumborg, AAFC)

however, depend on the amount of fuel used to grow the crop in the first place.

The materials most easily converted into ethanol are those with high starch content. Thus cereal grains, such as corn and wheat, are preferred for ethanol production. One study suggests that, if the CO_2 emitted in crop production are taken into account, use of corn-ethanol reduces

CO_2 emissions by about 40%, relative to the emissions from the gasoline it replaces. If the emissions of other greenhouse gases are also taken into account, then use of ethanol from corn or wheat reduces the global warming potential by 25–30%. In Canada, about 30 million litres of ethanol are currently produced annually from wheat and corn, reducing CO_2 emissions by about 33 Gg (thousand tonnes) per year. If Canadian ethanol production reaches the expected 265 million litres by the end of 1999, reductions in net CO_2 emission will be increased by the same proportion.

Though ethanol is most easily made from high-starch materials, new methods now also make it possible to make ethanol from fibrous matter, such as crop residues, forages, and crop wastes. An excess of about 2 Tg (million tonnes) of straw and chaff may be produced every year, beyond the amount needed for animal bedding and preventing soil erosion. If all this amount were used, it would produce about 500 million litres of ethanol and replace about 0.5 Tg (million tonnes) of fossil fuel CO_2 (equivalent to 2% of the emissions from fossil fuel used in agriculture). The process could also be used to produce ethanol from perennial grasses grown on marginal lands.

Still another way to reduce reliance on fossil fuel is to produce fuel for diesel engines ("biodiesel") from oilseed crops such as canola, flax, soybean, and sunflower. Although technically feasible, producing biodiesel is still much more expensive than producing fossil fuel.

Current status of methods to reduce carbon dioxide emissions

The C cycle is central to farming systems. Methods to reduce CO_2 emission rely mainly on managing that cycle more efficiently: recycling as much organic C as possible, minimizing disruption of soil, optimizing use of the sun's energy (via photosynthesis), and relying less on off-farm energy.

Because they promote efficiency, many of these methods also help sustain land resources and may even be profitable. As a result, they are being adopted for reasons quite apart from their benefits to atmospheric CO_2. For example, most farms in Canada now use less tillage than a generation ago, and an increasing proportion now use no-till practices. Similarly, the area of land devoted to summer fallow has fallen from about 11 million hectares in 1971 to about 6 million hectares in 1996. The use of these and other C-conserving approaches will likely continue to increase in coming decades.

The two general approaches—storing more C and relying less on fossil fuel— reduce CO_2 emissions over somewhat different periods. Storing C in soils has highest benefits early, in the first few years or decades, but net removal of CO_2 declines with time because it gets harder and harder to add additional C as soil C accumulates. Carbon dioxide savings from reduced fossil fuel, on the other hand, may seem rather small in the short term but can be significant when viewed over many decades. The net removal of atmospheric CO_2 from soil C gains is finite; that from reduced fossil fuel can continue indefinitely.

Reducing methane emissions

Methane, like CO_2, is part of the C cycle in farm ecosystems. It is released during decay of organic material when a shortage of oxygen prevents organic C from being completely converted to CO_2. Although both CH_4 and CO_2 are greenhouse gases, CH_4 has a much higher warming potential, so release of C as CO_2 is preferred.

Most CH_4 from Canada's farms comes from the livestock industry, either directly from the animals or from the manure they produce. A number of methods have been proposed to reduce emissions from these sources, some of which are already in use.

Reducing methane emissions from animals

Much of the CH_4 produced on farms is from ruminants—livestock such as cattle and sheep that have a rumen for digestion of feed. Specific practices that can reduce emissions from these animals include the following:

Change rations to reduce digestion time: Most CH_4 is released from the rumen, where feed is fermented in the absence of oxygen. The longer the feed remains in the rumen, the more C is converted to CH_4. As a result, any practice that speeds the passage of feed through the rumen will reduce CH_4 production. One study with steers showed that, when scientists increased the passage rate of matter through the rumen by 63%, CH_4 emission fell by 29%. The passage of feed through the rumen can be hastened by

- using easily digestible feeds grains, legumes, and silage

Effect of feed additives on methane emissions from dairy cows

Scientists at AAFC measured CH_4 emissions from dairy cows in a barn over 3 years with an automatic gas sampling system. In one trial, 95 to 100 cows were fed a total mixed ration (TMR) consisting of concentrate and ensiled forage (35:65 on a dry matter basis) and produced an average of 26.8 kg of milk per cow per day. After a control period, monensin was added to the ration. There was an immediate decrease in CH_4 emissions. At the same time milk production increased and daily feed consumption decreased, indicating an increased efficiency in feed usage. The effects of feeding monensin lasted 2 months after it was removed from the ration. There was, however, indication that rumen bacteria became resistant to monensin when a second feeding trial was conducted 5 months later. The use of monensin in dairy feeds is under consideration by regulatory authorities but has not yet been approved. This feed additive has been used in beef cattle since 1975. These results show that feeding additives can significantly decrease CH_4 emissions by dairy cows. However, further work is needed to resolve rumen microbial resistance and to develop a rotational system of feed additives to overcome this possibility.
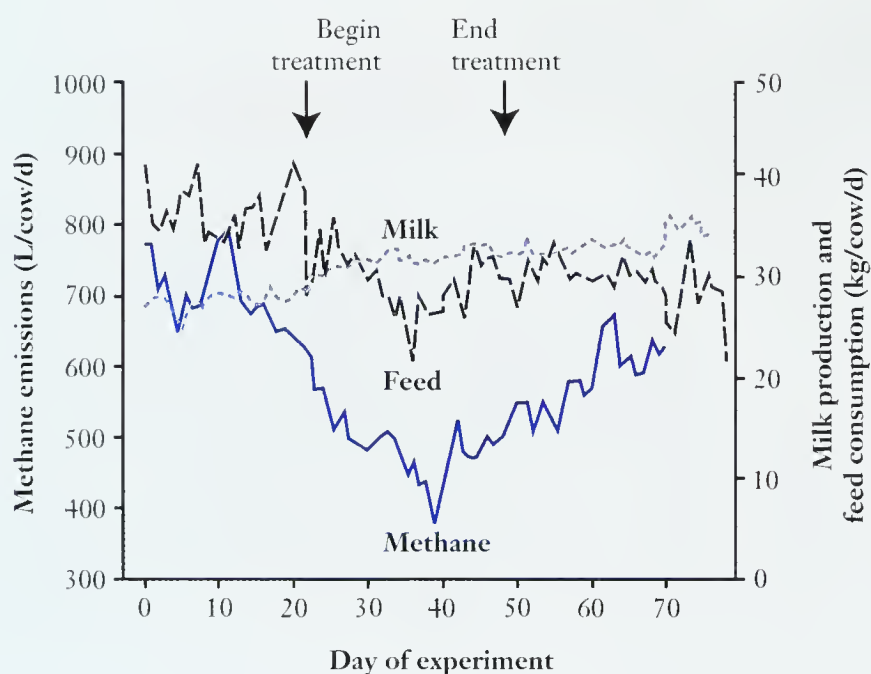
(H. Jackson and F. Sauer, AAFC)

- harvesting forages at an earlier, more succulent growth stage

- chopping the feed to increase surface area

- minimizing use of fibrous grasses and hays

- feeding concentrated supplements as required.

Add edible oils: Adding canola, coconut, or other oils to the diet may reduce CH_4 production by inhibiting the activity of CH_4-producing bacteria. Though quite effective, this practice may not always be economical.

Use ionophores: Ionophores are feed additives that inhibit the formation of CH_4 by rumen bacteria. Already widely used in beef production, they can reduce CH_4 emission. However, some evidence suggests that rumen microbes can adapt to a given ionophore, lessening its effect over time. For long-term effectiveness, it may be necessary to use a rotation of different ionophores.

Alter the type of bacteria in the rumen: In the future it may be possible to introduce into the rumen genetically modified bacteria that produce less CH_4. Though research efforts are promising, such inoculants are not yet commercially available.

Improve production efficiency: Any practice that increases the productivity per animal will reduce CH_4 emissions because fewer animals are needed to achieve the same output. For example, giving animals more feed may increase CH_4 production per animal but reduce the amount of CH_4 emitted per litre of milk or per kilogram of beef. Any other practice that promotes efficiency will likewise reduce CH_4 emission per unit of product.

Many of these practices are already practical and economical. When used together, they can lower loss of energy through CH_4 release from about 5–8% of the gross feed energy to as

low as 2 or 3%. Because they increase feeding efficiency, these practices also often have economic benefits. Consequently, they are already widely used on many farms, especially in dairy herds and beef feedlots.

Reducing methane emissions from manures

Most of the CH_4 from manure is produced during storage. When the manure is stored as liquid or in poorly aerated piles, lack of oxygen prevents complete decomposition to CO_2, resulting in the release of CH_4. Most ways of reducing emission, therefore, involve slowing the rate of decomposition, providing better aeration, or reducing the length of storage. Specific methods include the following:

Use solid- rather than liquid-manure handling systems: Oxygen supply is usually better in solid manure, which encourages CO_2 to form rather than CH_4.

Apply manure to land as soon as possible: The longer manure is left in feedlots, in stockpiles, or in slurry tanks and lagoons, the more CH_4 will be emitted. Frequent applications to the land can therefore reduce emissions. Unfortunately, storing the manure is sometimes unavoidable because the land is frozen, too wet, or planted to crops.

Minimize amount of bedding in manure: Manure with less bedding, such as straw, contains less C that can be converted to CH_4.

Keep storage tanks cool: Lowering the temperature of tanks, by insulating or placing them below-ground, slows

Cattle management systems

Producers feed and manage their cattle in different ways during different stages of the production cycle. The amount of greenhouse gas emitted depends on the system used and the stage in the cycle. Management systems can be compared in terms of net emissions; for example, grams of CH_4 emitted per kilogram of milk or beef produced. Feeding cattle grain instead of forage reduces CH_4 emissions. But feed type is only one factor to be considered in selecting a management system. For example, the use of forages in a feeding system encourages land to be used for perennial forage, rather than for annual crop production which results in greater soil C losses. Manure management and its greenhouse gas emissions must also be considered when determining an optimum management system.

(P. Strankman, Canadian Cattlemen's Association and K. Wittenberg, University of Manitoba)

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Improved manure storage can reduce greenhouse gas emissions

Traditionally, manure is stored during summer and winter and is applied to the field in early fall or spring. Summer is usually the season of highest gas production because warm temperatures enhance microbial activity in stored manure. Anaerobic storage favors CH_4 production, whereas aerobic storage produces CO_2 and N_2O.

Scientists measured greenhouse gas emissions from beef and dairy manure each stored in three ways: compost, slurry, and stockpile. Methane and N_2O emissions, expressed in CO_2 equivalents, were always smaller for compost than for the other storage methods. For dairy manure, slurry emitted 1.9 times more greenhouse gas than the compost. Stockpiled manure emitted 1.5 times more greenhouse gas than the compost. Methane was the dominant gas in both the slurry and the stockpile. Nitrous oxide represented most of the compost emissions and a significant portion of the stockpile emissions.

For beef manure, emissions of CH_4 and N_2O were much lower than from dairy manure. Emissions of CH_4 and N_2O were 1.3 times higher from stockpiled beef manure than from compost and 4–6 times higher from slurry than from compost.

These results indicate that aerobic storage such as composting may limit the greenhouse gas emissions. On the other hand, creating fully anaerobic conditions during storage promotes emission of CH_4 that could be collected and used as a fuel.

Bins in which the manure was stored either as slurry, stockpiled, or for composting. A large enclosure was installed over each bin, and the gas emissions were monitored for a given time.

(E. Pattey, AAFC)

decomposition, thereby reducing emission of CH_4.

Burn methane as fuel: Methane is a very effective fuel; indeed, it is the main constituent of natural gas. In some countries, CH_4 from stockpiled manure is already collected and burned. In Canada, this approach may not yet be widely practical or economical but is receiving growing interest. Burning CH_4 converts it to CO_2, which has a much lower warming potential.

Avoid landfilling manure: Although most manure in Canada is applied to land, small amounts are still disposed of in landfills. Because decomposition in landfills is usually oxygen-starved, large amounts of CH_4 can be emitted from this practice. Furthermore, placing it in landfills wastes valuable nutrients in the manure.

Aerate manure during composting: To make it easier to transport, manure is sometimes composted before applying it to the land. The amount of CH_4 released during composting can be reduced by aerating the stockpiled manure, either by turning it frequently or by providing a ventilation system inside the pile. Aeration encourages complete decomposition to CO_2 rather than release of C as CH_4.

These methods can reduce, to some extent, the CH_4 emitted from animal manure. Because of high densities of livestock in some areas, and the high cost of handling and transportation, managing manure still remains a challenge. Other ways to reduce emissions may still be needed.

Reducing nitrous oxide emissions

Much of the N_2O emitted from farmland is produced when excess NO_3^- in soil undergoes denitrification, either on farmland or after it is leached away. Farmers can reduce these emissions by preventing build-up of NO_3^- or avoiding soil conditions that favor denitrification. Some N_2O is also emitted when NH_4^+ is converted to NO_3^- (nitrification). Adding less NH_4^+ or slowing the rate of nitrification can reduce emissions from this source. The best way to reduce N_2O losses is to manage the N cycle more efficiently, thereby avoiding the buildup of excessive NH_4^+ or NO_3^-.

Specific ways of reducing N_2O emission vary for farming systems across Canada, but examples include the following:

Match fertilizer additions to plant needs: The best way to reduce N_2O emission may be to apply just enough N so that crops can reach maximum yield without leaving behind any available N. A perfect match is rarely achievable, but the synchrony can often be improved by basing fertilizer rates on soil tests and estimates of N release from residues and organic matter. In fields where fertility needs vary, applying N at different rates across the landscape ("precision farming") may also improve the match between amount applied and the amount taken up by crops.

Avoid excessive manure application: Heavily manured land can emit a lot of N_2O because the manure adds N and available C, both of which promote denitrification. Moreover, manure is often applied to land as a means of disposal, so that rates can be excessive.

New technology of manure treatment

Scientists have introduced a new manure treatment process based on the use of anaerobic microorganisms in sequencing batch bioreactors (ASBR). Trials performed in the laboratory showed that the ASBR technology is very stable and versatile and works well at low temperatures (between 10 and 20°C). Furthermore, the bioreactors need to be fed only once a week, during regular manure removal.

The airtight reservoir needed to maintain anaerobic conditions in the bioreactor completely eliminates any emissions of greenhouse gas during treatment and storage. The biogas can be recovered and used for energy on the farm.

The technology also has other interesting benefits. It deodorizes and stabilizes the swine manure slurry leading to the degradation of most of the 150 odor-causing substances in the manure. Furthermore, this technology increases the availibility of nitrogen and phosphorus to crops and reduces the need for chemical fertilizers.

Anaerobic sequencing batch bioreactor.

(D. Massé and F. Croteau, AAFC)

Applying the manure at rates that just supply plant demands can greatly reduce N_2O emissions from this source.

Optimize timing of nitrogen application: When the N is applied is as important as the rate of addition. Ideally, farmers should apply N just prior to the time of maximum uptake by the crop.

Wherever possible, they should avoid applying fertilizer and manure in fall. Similarly, they should time the plough-down of N-rich crops, like legumes, so that N release from the residues coincides with subsequent crop demands.

Improve soil aeration: Denitrification, and hence N_2O emission, is favored by the low oxygen levels that usually occur in saturated soil. As a result, farmers can reduce emission of N_2O by managing soil water—draining soils prone to water-logging, avoiding over-application of irrigation water, and using tillage practices that improve soil structure.

Use improved fertilizer formulations: Some research suggests that certain forms of fertilizer emit more N_2O than others. Highest emissions may occur from anhydrous ammonia; lowest from forms containing NO_3^-. This finding suggests that, by selecting appropriate fertilizers, farmers could reduce N_2O release. However, the differences among forms of fertilizer have not yet been widely verified in Canada. Another option is to use slow-release fertilizers, such as sulfur-coated urea. These forms release available N gradually; they feed the crop yet prevent available N from accumulating. Though effective in reducing N_2O emissions, slow-release forms may only be economical for high-value crops.

Use appropriate fertilizer placement: Placing fertilizer in close proximity to crop roots can improve the efficiency of nutrient use, allowing the farmer to achieve high yields with lower rates of application. On the other hand, placing the fertilizer too deep in the soil, or concentrating forms like urea in bands, may increase N_2O emissions.

Use nitrification inhibitors: Certain chemicals, applied with fertilizers or manures, inhibit the formation of NO_3^- from NH_4^+. Their use may suppress N_2O formation in several ways: it reduces N_2O formation during nitrification, it prevents denitrification of accumulated NO_3^-, and, because NH_4^+ does not leach easily, it prevents loss of N into groundwater where denitrification could occur.

Use cover crops: Where the growing season is long enough, farmers can sow crops after harvest to extract excess soil NO_3^-, which prevents it from leaching or converting to N_2O.

Lime acid soils: Because it is favored by acidity, N_2O emission can be suppressed by applying neutralizing lime to acid soils.

Reduce tillage intensity: Though results are still inconsistent, some studies in Canada suggest that N_2O emission may be lower in no-till than in conventional tillage. If confirmed, this observation may point to no-till as a method of reducing emissions, at least in some soils.

These practices can help reduce N_2O emissions in many settings. Because N_2O fluxes are so sporadic, however, all these practices cannot yet be recommended with confidence across Canadian soils and cropping systems. But those that improve the efficiency of N use are often already justified for reasons quite apart from reduced N_2O emission. Fertilizers account for about 9% of production costs on farms, and any method that reduces N losses has economic benefits.

Putting it all together

For simplicity, we often discuss methods of reducing emissions for each gas separately. But the C and N cycles are tightly interwoven; a change in farming practice that reduces emission of one gas almost always affects another. Whether or not a new practice helps alleviate the greenhouse effect depends on the net effect on emission of all gases and the relative warming potential of each. A few examples may help to illustrate some of the complex interactions.

One of the ways to reduce CO_2 emissions is to farm more intensively: to eliminate summer fallow, to use higher-yielding varieties, and to aim for higher productivity. Such practices can increase stored C by producing higher amounts of residue that become soil organic matter. At the same time, however, the new, more-intensive system may require higher inputs, including fertilizers, to maximize yields. And those higher inputs of fertilizer may increase N_2O emissions. The overall effect of the new practice must therefore take into account the change in soil C, the CO_2 cost of making the added inputs, and any increase in N_2O emission. Because N_2O is such a potent greenhouse gas, a small increase in emission rate (say 1 kg N per hectare per year), will offset a comparatively high rate of soil C accumulation (~130 kg C per hectare per year).

The evaluation becomes even more complex if we include animals. Suppose, for example, we opt to allocate greater land area to producing forages. This effect would have pronounced benefits for storing soil C. Furthermore, it would reduce fertilizer requirements (and N_2O emissions from that fertilizer), because nutrients are effectively recycled back to the soil as manure. On the other hand, much of the C in that system would be fed to animals, and a portion would be released as CH_4. Furthermore, some CH_4 and N_2O would be produced from manure. Thus, with one management change, we have affected emission of all three gases, sometimes both negatively and positively. And to know the net effect of the practice, we must consider all three and their relative warming potentials.

We cannot yet grasp all the interactions among gases, nor are our models sophisticated enough to predict them. At present, however, it may be sufficient to recognize that all are part of a complex web, and any attempt to reduce emissions of one may affect the others. Often, the net effect may still be overwhelmingly positive; for example, it may be that the increased soil C from a livestock-based system more than offsets any increase in CH_4 emission. Indeed, sometimes the effects may even be mutually positive; no-till, for example may increase soil C, reduce CO_2 from fossil fuel, and perhaps even reduce N_2O emissions. Similarly, more efficient use of manures, can almost certainly reduce N_2O and CH_4 emissions, while reducing CO_2 costs of fertilizer manufacture.

A final consideration is that the various practices aimed at reducing greenhouse gas emissions may work over different periods. For example, efforts to increase soil C gains may show largest response in the short term, say one or several decades, but rates of C gain may diminish thereafter because each new increment of C

becomes harder and harder to achieve. In comparison, efforts to reduce CH_4 emission from ruminants, N_2O emission from soils, or CO_2 emission from fossil fuels may have only small effects in the short term but achieve highest effect over many decades because the benefits accrue indefinitely.

Other effects of practices that reduce greenhouse gas emissions

We cannot judge the attractiveness of various management practices solely on how well they reduce greenhouse gas emissions. Other factors that come into play include their practical feasibility, economic cost, effect on soil quality, and influence on the whole environment (Table 16). When all these factors are considered together, many of the proposed practices have favorable ratings across the spectrum. For example, reducing tillage intensity has either favorable or neutral effects on all the criteria (though, clearly, these tentative ratings will vary for different areas of the country). Some practices, such as using nitrification inhibitors, have numerous benefits but their use may be limited by cost. Most of the proposed methods of reducing greenhouse gas emissions have favorable effects on soil quality and adjacent environments.

Many of these other considerations are as important as any benefits to the atmosphere. The adoption of proposed practices will be driven at least as much by these factors as by the desire to reduce greenhouse gas emissions.

Table 16 Projected effects of various agricultural practices that affect greenhouse gas emissions

Practice	Effect on GHG emission			Other considerations			
	CO_2	CH_4	N_2O	Feasibility	Economics	Soil quality	Environment
Reduced tillage intensity	++	0	?	+++	+	++	++
Reduced summer fallow area	+++	+	-	++	-	++	+
Improved manure management	0	+	++	++	--	+	++
Improved feeding rations	-	++	0	+	++	0	0
Improved drainage/irrigation	+	+	++	+	+	+	-

+ beneficial   0 no effect   - detrimental
number of + or - signs indicate magnitude of effect

3. Ozone

Ozone is a bluish gas, with a sharp, irritating odor. It occurs naturally in the upper atmosphere ("stratosphere"), where it forms continually from reactions promoted by the sun's radiation. Unlike the more common gas oxygen (O_2), O_3 is highly unstable, reacting with other molecules in the atmosphere, so that its lifetime is only hours or days. The O_3 in the upper atmosphere serves a useful function by filtering out harmful UV radiation. However, pollutants entering the upper atmosphere deplete the O_3, thereby increasing the intensity of UV radiation at the earth's surface.

Ozone also occurs naturally near ground level, where it occurs at concentrations of 25–40 parts per billion by volume (ppbv). Along with other pollutants (e.g., nitrogen oxides, peroxides, peroxyacetyl nitrate, and particulate matter), ground-level O_3 forms smog. The ill effects of smog on human health are reasonably well known, but its effect on plants has received little publicity. Yet, according to some estimates, O_3 causes tens of millions of dollars worth of damage to crops in Canada annually, mainly in the Fraser Valley of British Columbia, the Quebec–Windsor corridor, and the southern Atlantic region.

Thus O_3 is unique among atmospheric gases: in the upper layer, it is highly beneficial; near ground level, it is a serious pollutant. Ironically, human activity has depleted O_3 in the upper atmosphere but increased its concentration at ground level. In this section, we describe the problem of ground-level O_3; the problems arising from depleting O_3 in the upper atmosphere we discuss later.

Source of ground-level ozone

Low concentrations of O_3 occur naturally at ground level, formed in the presence of sunlight by reactions between nitrogen oxides and volatile organic compounds (VOCs) (Fig. 25). Natural sources, such as vegetation and soils, release these compounds at low concentration. But human activities have increased the amounts released: VOCs from petroleum, chemical industries, and transportation and nitrogen oxides from combustion in power stations and automobiles. Consequently, O_3 is more concentrated and more smog occurs in densely populated and industrial regions. The health and environmental hazards of smog have prompted federal and provincial governments to impose limits on emissions of nitrogen oxides and VOCs into the atmosphere.

Ozone concentration measurements

Ozone concentrations are measured at only about 100 locations in Canada as part of the air-quality network operated by the Atmospheric Environment Service of Environment Canada. To see how representative these measurements are, scientists used low-level flights to measure ozone concentrations upwind and downwind of the city of Montreal.
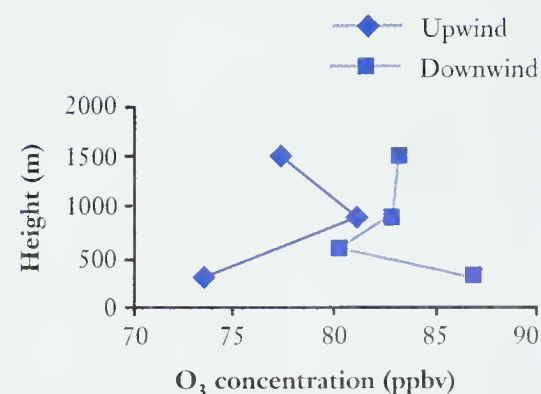
The ozone concentrations were found to be greater downwind than upwind of the city at all altitudes. Consequently, ozone concentrations reported by the network may have to be adjusted depending on the location of the measurement.

(J.I. MacPherson, NRC; R.L. Desjardins, AAFC)

Figure 25

Conceptual diagram showing ground-level O_3 formation. Volatile organic compounds (VOCs), emitted into the atmosphere from vegetation and artificial sources, react with NO_x in the presence of sunlight to form O_3.

Effect of ozone on plants

Ozone enters plant leaves via stomata, tiny valved pores on the leaf surface that regulate the exchange of gas between plant and air. During the day, the stomata are normally open to permit entry of CO_2 for photosynthesis. Unfortunately, at this time O_3 levels are highest.

Once inside the leaf, O_3 oxidizes molecules in cell membranes, causing the membranes to break down. Because O_3 occurs naturally in the atmosphere, plants have evolved some protective mechanisms, including "antioxidants" like vitamins C and E, and specialized proteins (enzymes) that repair injury from O_3. But at higher O_3 levels, these protective mechanisms are inadequate to prevent injury to tissues.

Ozone can cause direct damage to leaf tissue, often visible as flecking,

Major Canadian cities now experience, on several days each year, O_3 levels above the maximum acceptable air-quality level of 82 ppbv for 1 hour. Values of 170 ppbv have been recorded at several locations in Ontario. Stable air conditions during summer and fall especially favor the formation of smog. In light winds, smog can spread over large areas, often affecting regions on both sides of the Canada–US border. Because it requires sunlight to form, O_3 tends to diminish in concentration at night, whereas other smog constituents are unaffected.
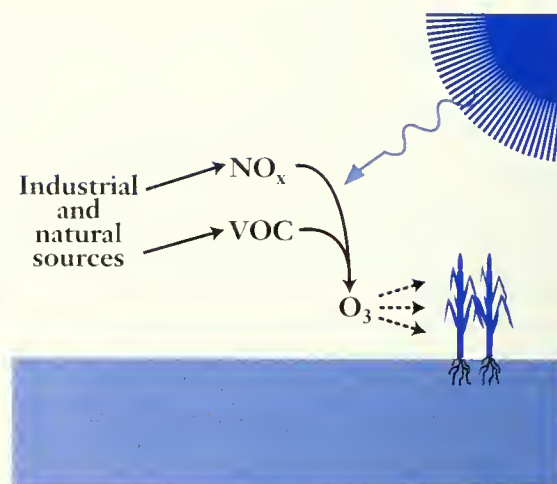
bronzing, water-soaked spotting, and premature aging of leaves. Furthermore, high O_3 concentrations may cause the stomata to close, which cuts the flow of CO_2 and shuts down photosynthesis. As a result of the direct damage and the reduced photosynthesis, yields of some plants can be dramatically reduced by long-term exposure to elevated O_3 levels.

Although scientists have studied the effects of O_3 on various crops in Canada and elsewhere for more than 40 years, fluctuations in O_3 concentrations in polluted air pose major difficulties in providing reliable estimates of the damage caused to crops.

Ozone exposure and absorption by crops

Air pollution monitoring sites across Canada routinely measure ground-level O_3 concentrations. But concentrations alone are insufficient to evaluate potential damage to plants. Plants are less sensitive at night and during periods of slower growth. Temperature and moisture conditions also affect sensitivity. Consequently, we must measure actual O_3 absorption to assess effects on plants.

One way of estimating O_3 absorption is to measure the instantaneous O_3 concentration in downward- and upward-moving air, using sensors mounted on towers. If the concentration is greater in air moving down than in air moving up, that indicates O_3 absorption: the greater the difference, the higher is the absorption rate. This approach allows almost continuous

Ozone and leaf stomata

When plants take in CO_2 for photosynthesis through their stomata, ozone can also enter. The ozone causes the cells surrounding the stomata to decrease in turgidity, which reduces the size of the opening. This closing helps to protect the plant from further ozone damage. Once inside the leaf, however, ozone is highly reactive and can destroy the leaf cells, which can substantially reduce crop yield.

20 μm

Diagram of O_3 flowing into a leaf via a stomate and causing damage by oxidizing cell walls and mesophyl

Stomata open in light — CO_2 O_3 — Stomata closed at night

O_3

Cell membranes

Cells

Chlorophyl
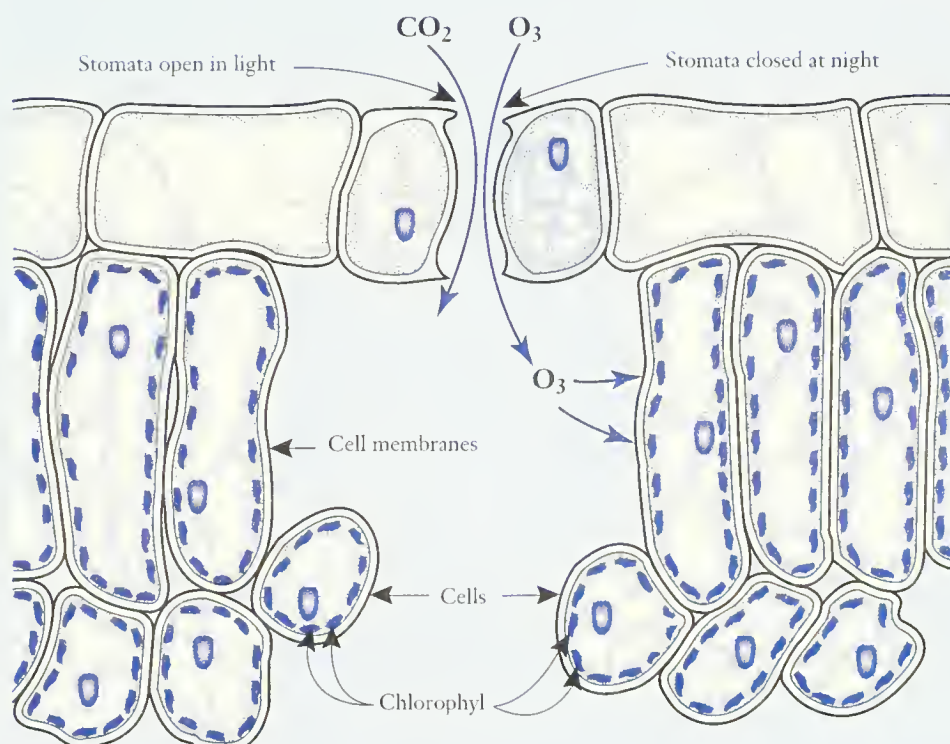
measurement of O_3 flux and provides daily and seasonal patterns of absorption. In one study, for example, the O_3 flux above a soybean field increased during the day but then dropped sharply when the stomata began closing (Fig. 26). Because the opening and closing of stomata is controlled by water stress, there is a strong relationship between O_3 absorption and transpiration (the amount of water lost from the plants).
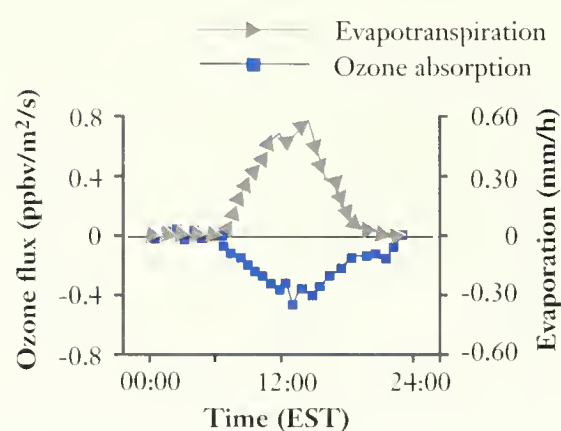

Figure 26

Ozone absorbed and water transpired by soybean on a sunny day in August in Ottawa. (E. Pattey, AAFC)

For larger-scale measurements, instruments can be mounted on aircraft, as described for CO_2, N_2O, and CH_4 measurements. Aerial O_3 surveys have already been made for many crops, weather conditions, and O_3 concentrations. One observation from this approach is the strong relationship between O_3 absorption and the amount of green vegetation.

The scale can be increased still further by using satellites. Scientists can calculate transpiration from environmental conditions and can obtain a "greenness" index from satellite images. Because of its close relationship

to transpiration, O_3 absorption can then be estimated for the entire growing season on large areas, using O_3 concentrations from measurement networks (e.g., Fig. 27).
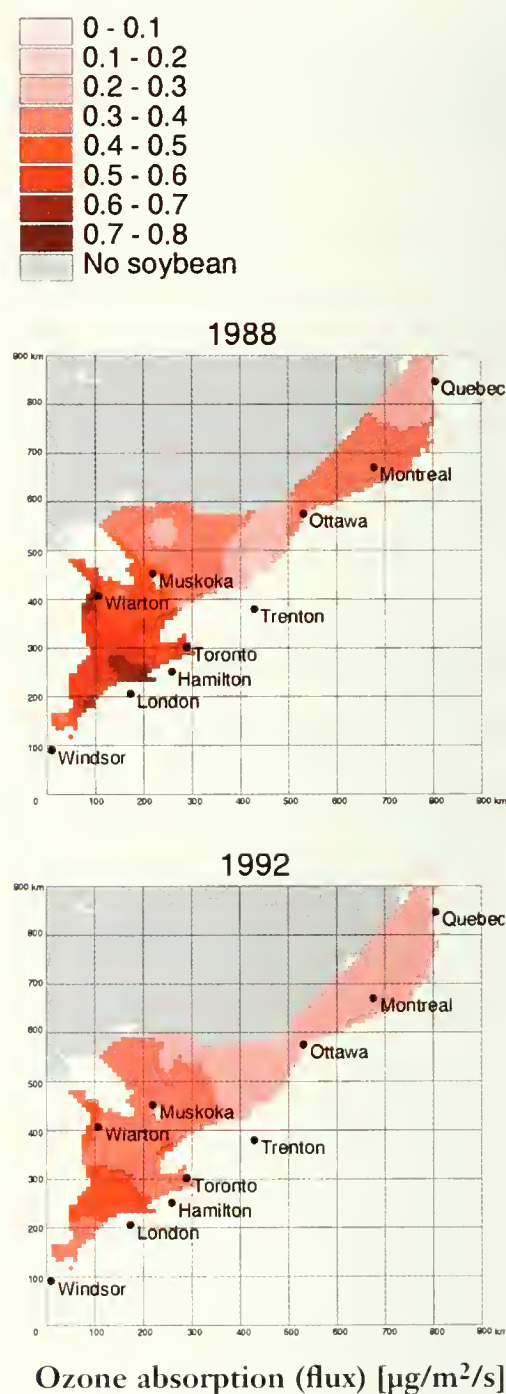

Ozone absorption (flux) [µg/m²/s]

Figure 27

Estimated O_3 absorbed by soybeans in the Windsor–Quebec corridor, 1988 and 1992. (R.L. Desjardins and Y. Guo, AAFC)

This approach, however, only estimates average absorption over the long term and cannot describe the short-term

fluctuations associated with daily changes in moisture stress or plant development. Furthermore, it tends to "dilute" relatively brief exposures to high concentrations that are likely to be most harmful to plants. Nevertheless, these estimates provide a useful indicator of potential plant damage.

Measuring plant response to ozone

The simplest way to measure plant response to O_3 is to grow them inside open-top enclosures into which O_3 is then continually released in concentrations that reflect the daily variations. This method allows researchers to evaluate the effect of several concentrations of O_3 (typically up to three times that in outside air) as well as those of other gases or pollutants that can be added simultaneously.

In a less disruptive approach, called the "zonal air pollution system" (ZAPS), a series of pipes over the crop continuously releases O_3 into the plant canopy at various rates in different plots. This method avoids some of the artificial conditions inside chambers but costs more. As well, the maximum enrichment achieved by this technique is not high, because of the continual mixing with untreated air.

Open-topped enclosures and ZAPS are useful for detailed research studies, but they do not provide information on O_3 damage over large areas. Networks of instruments that continuously record O_3 concentrations exist in many populated regions but are sparse in rural areas. To provide O_3 information in such areas, scientists use "biomonitors" or "passive" monitors.

Open top enclosures, zonal air pollution system, and biomonitors.

Biomonitors are plants, like the tobacco variety "Bel-W3," that are highly sensitive to O_3. They are set out throughout a region and then inspected regularly for flecks of dead-tissue, which are symptoms of injury from O_3. The biomonitors therefore provide an estimate of O_3 absorption by leaves and indicate potential damage to other less-sensitive crops, even though these may show no visual signs of stress. Passive monitors are simply filter papers treated with indigo dye. When exposed to O_3, the dye changes color. The degree of color change provides an index of the total exposure to O_3 during the period.

Observations from biomonitors and passive monitors can be related to potential crop effects by placing these monitors inside a ZAPS along with other crop plants. "Flecking" of biomonitor leaves or color change in passive monitors can then be directly related to crop damage. Using these relationships, scientists can use biomonitors and passive monitors placed throughout a region to estimate yield effects of O_3 absorption throughout that area. Researchers have used an extensive network of this type to monitor O_3 effects on yields in the Fraser Valley, a highly populated area with intensive agriculture (Fig. 28).

Examples of crop response to ozone

The effect of O_3 has already been widely studied and some extensive reviews are now available. Here we present only a few examples to illustrate the nature and objectives of some recent research.

Effect of ozone on broccoli

Broccoli is a high-value crop that is harvested about 6–8 weeks after transplanting. Rapid leaf growth after transplanting feeds the developing flower head. Any stress on leaves
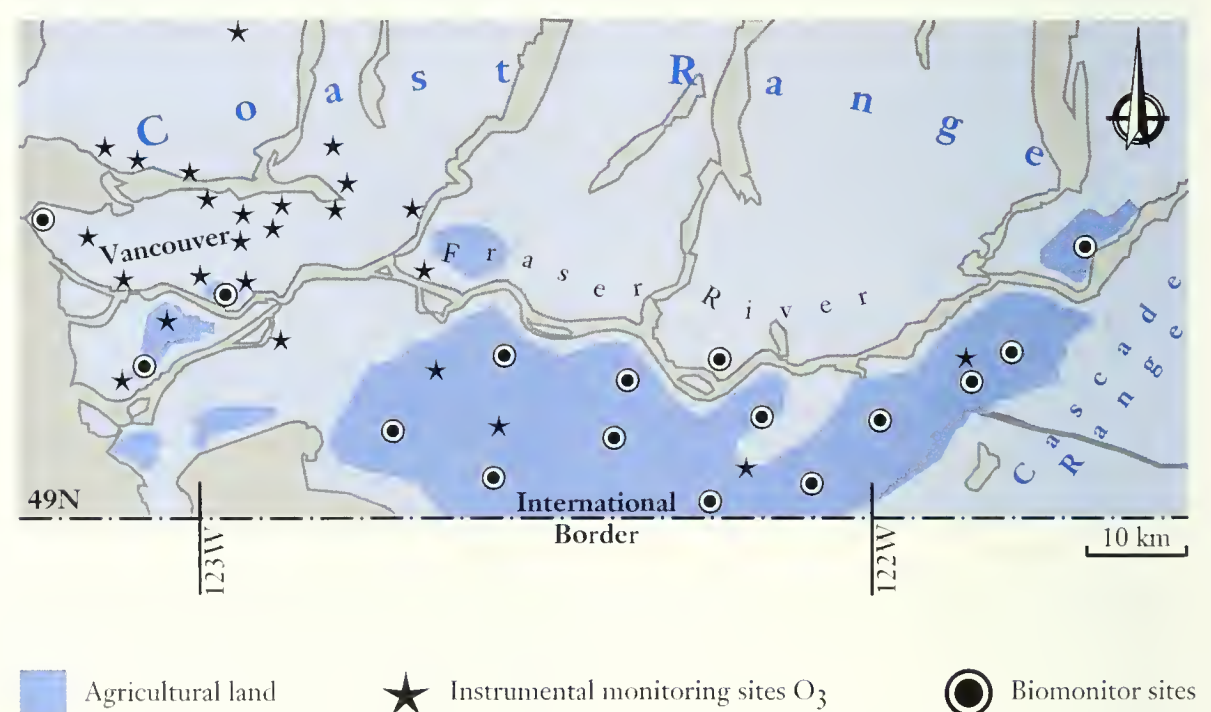

Figure 28
Map of the ozone monitoring network in the Fraser Valley, B.C. (P. Bowen, AAFC)

during this time usually results in smaller heads and lower yield. Studies using a ZAPS showed that ozone injures leaves in two ways: it kills some of the tissue directly (Fig. 29a) and makes other tissue prone to attack by downy mildew, a fungal disease (Fig. 29b). Severity of damage was directly related to O_3 enrichment.

a

Broccoli is sensitive to O_3

b
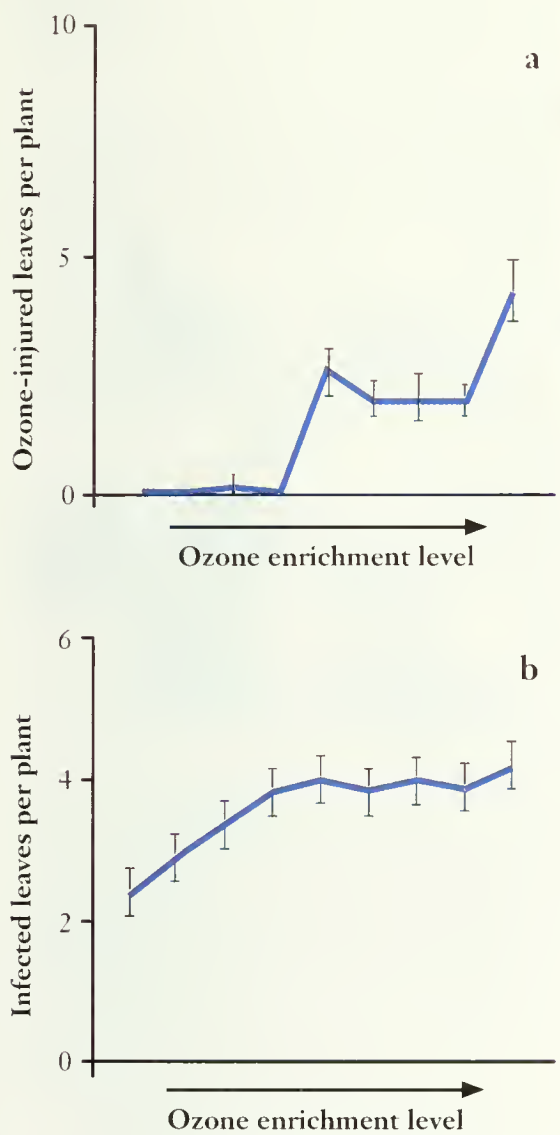
Figure 29

**Response of broccoli to O_3:
a) O_3 injury to broccoli leaves;
b) Leaves infected with downy mildew on broccoli exposed to O_3. (V.C. Runeckles, University of British Columbia, Vancouver, B.C.)**

Effect of ozone on orchardgrass

Orchardgrass is the main feed of dairy cows in the Fraser Valley. The grass can be harvested for hay up to five times a year. Loss in yield at any harvest depends on O_3 exposures received during the preceding growing period. One study examined the relationship between level of O_3 and orchardgrass yield in a ZAPS (Fig. 30). The data show how yield decreased as the exposure increased (reported as the number of days during which hourly concentrations exceeded 50 ppbv). Because orchardgrass is a perennial, its early spring growth partly depends upon the reserves stored in the roots and stems during the previous growing season. Studies over successive years have shown that exposing plants to O_3 in the fall suppresses yield the next spring.

Figure 30

Dry matter yield of orchardgrass as affected by exposure to O_3. (V.C. Runeckles, University of British Columbia)

Effect of ozone on strawberry

Increased exposure of strawberry plants to O_3 reduces the number and weight of good fruit. A network of calibrated passive monitors in the Fraser Valley indicated that fruit losses can be as high as 15%.
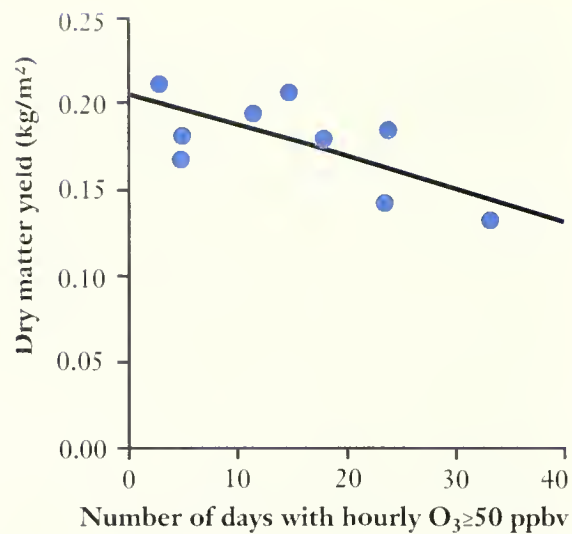
Effect of ozone on lettuce

Visual appearance of leaves affects the market value of crops like lettuce. In ozone exposure studies, lettuce leaves showed no visible symptoms. Even at the highest exposure levels, the crop appeared healthy. Surprisingly, however, O_3 reduced head size and weight, indicating that O_3 damage can be subtle and detectable only with careful scrutiny.

Combined effect of ozone and carbon dioxide on alfalfa

Under high O_3 concentrations, alfalfa grows more slowly and competes less against weeds. Like orchardgrass, exposing alfalfa to O_3 in the fall of one

year may reduce its yield the year after. Its ability to survive cold winters, however, does not seem to be affected. One study measured the effects of increasing both O_3 and CO_2 concentration on alfalfa growth. Increasing the CO_2 concentration actually increased the tolerance of alfalfa to high concentrations of O_3 (Fig. 31), probably because the stomata are partially closed at high CO_2 levels. This finding may have important implications if, as expected, atmospheric CO_2 concentration doubles some time in the next century.
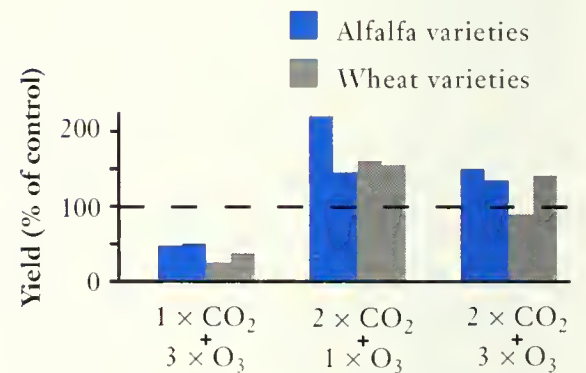
Figure 31

Relative effects of O_3 and CO_2 on yield of alfalfa and wheat. The values in the legend indicate concentration relative to background. (G. Allard, Université Laval)

Differences in ozone tolerance among varieties

Plants show a wide range of tolerance to O_3 in the air, even among varieties of the same crop. Comparing two alfalfa varieties ("Apica" and "Team") in open-topped enclosures for 2 years showed that "Apica" was unaffected by low O_3 levels but was strongly affected by higher concentrations in both years. "Team" was almost unaffected in a cool and rainy summer, but was affected almost as severely as "Apica" in a warm

and sunny summer. In a similar study, spring wheat varieties "Bluesky" and "Opal" were exposed to air with no O_3, and 1.0, 1.5, and 3.0 times the ambient O_3 concentration (Fig. 32). "Opal" appears more tolerant to O_3. The pattern of tolerance was different for the 2 years tested. This finding suggests not only that varieties have different tolerances to O_3 but also that weather conditions affect those tolerances.

Figure 32

Yield response of two wheat cultivars to increasing concentration of O_3.
(G. Allard, Université Laval)

New crop varieties tolerate disease better, are better adapted to local conditions, and generally produce higher yields. Do they also do better under higher O_3 concentrations? One study compared the O_3 tolerance of wheat varieties released at various times, from the 1950s (when O_3 concentrations were generally lower) to the early 1990s. Under current O_3 concentrations, the newer varieties yielded better, but, at higher O_3, they

fared worse. One explanation is that newer varieties need more CO_2 to support higher rate of photosynthesis; hence, the stomata stay open longer and absorb more O_3. Another explanation is that the improved yield of newer varieties results from a higher ratio of grain to leaf tissue. With relatively less leaf area to absorb CO_2 for grain production, leaf injury by O_3 may be more pronounced.

Environmental interactions

Unfortunately, crops are rarely exposed to only one pollutant. Plants growing in high O_3 concentrations may also suffer injury from sulfur dioxide, nitrogen oxides, acid rain, and UV radiation. The net effect of exposing plants to more than one pollutant may be equal to, greater than, or less than the sum of their individual exposures. The effects are further complicated by crop type, time of exposure, weather conditions, previous exposure, and other environmental stresses. Consequently, recent studies have only provided some knowledge about the potential effects of O_3 on a few major crops and regions.

4. Other links between agriculture and the atmosphere

Although CO_2, N_2O, CH_4, and O_3 have attracted much attention recently, agriculture also releases other materials into the air, including ammonia, other odors, aerosols, nitrogen oxides, and pesticides. As well, agriculture may be affected by changes to stratospheric O_3. Many of these issues have not yet been thoroughly studied in Canada. Our main aim is to identify the potential issues and point to some possible effects.

Ammonia

Current farming practices rely heavily on inputs of extra N, most of which ultimately derives from atmospheric N_2. These high inputs help sustain food production, but they also stress the natural N cycle, resulting in "leaks" of N into the environment. The release of N_2O is one such leak; another is the emission of ammonia (NH_3).

Background

Globally, agriculture is the main source of atmospheric NH_3 from human activity. Much of this NH_3 comes from livestock production. In parts of Europe, notably the Netherlands, NH_3 emissions from animal production are so high that they warrant strict regulations. In Canada, the problem is not yet as acute, except perhaps in local areas with high livestock numbers.

Ammonia is a colorless gas, lighter than air, with a sharp odor. In remote areas, away from sources, it occurs in the atmosphere at very low concentrations (less than 0.01 ppmv). In areas near intensive livestock production, however, concentrations may be much higher, sometimes well above the threshold at which it can be detected by smell (~0.6 ppmv).

Unlike N_2O, NH_3 is highly reactive and remains in the atmosphere only a short time. It reacts quickly with water, forming ammonium (NH_4^+). Thus any moist surface—soil, plants, or open water—readily removes NH_3 from the air, as long as the surface is neutral or acidic in pH. In the air, NH_3 can dissolve in precipitation and fall to the earth as NH_4^+, or it can be oxidized or dissociated by sunlight. As well, NH_3 can react with pollutants such as acidic sulfates and nitrates, forming tiny particles of ammonium nitrate or ammonium sulfate. Because NH_3 is so reactive, its concentrations are localized: high near sources and almost negligible elsewhere. In an area near Lethbridge, Alta., for example, high concentrations were found close to feedlots, but relatively low values just 1 km away.

Ammonia has many undesirable effects at high concentrations. Near sources, where concentrations are high, it produces an unpleasant odor and may affect human and animal health. Local deposition of emitted NH_3 may "fertilize" the land, but excessive amounts can result in leaching of N and contamination of ground- or surface-water. Excessive NH_3 may even be converted to N_2O, thus

indirectly contributing to the greenhouse effect.

Though many of the effects of NH_3 occur locally, it also has long-range effects. Ammonium particles, formed upon reaction with other N or sulfur compounds, can be carried long distances by wind before being deposited. Because N is often a growth-limiting nutrient, the deposition of this NH_4^+ can cause undesirable growth in lakes, alter forest growth, or disrupt sensitive ecosystems. When deposited on native grasslands, for example, atmospheric NH_3 or (NH_4^+) may favor the growth of some species at the expense of others, causing a shift in the mixture. Atmospheric NH_3 can also result in acidification because it accelerates the rate at which sulfur dioxide (SO_2) converts to sulfuric acid, leading to acid rain. The NH_3 itself produces acid when it undergoes nitrification, once deposited on soil as NH_4^+.

Because of its numerous potential effects, both near sources and in remote areas, NH_3 can be a serious pollutant and efforts to reduce its emission are warranted. Before examining possible ways of reducing emissions, however, it may be helpful to briefly review the sources of NH_3 in agriculture.
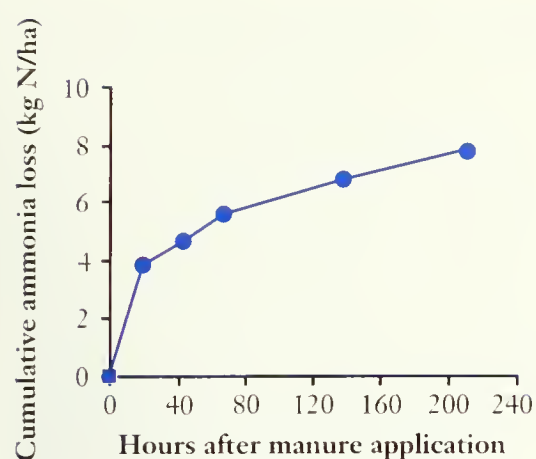
Agricultural sources of ammonia

The three main sources of NH_3 on farms are animal wastes, fertilizers, and crop residues. The first of these accounts for about 80% of agricultural emissions.

Of the N consumed by farm animals in feed, only a small proportion (roughly one-fifth) is retained by the animal; the rest is excreted in feces and urine. Some of this N (especially in urine) occurs as urea, a form easily converted to NH_3 and CO_2. As a result, a large proportion of the N in manure can be lost as NH_3 soon after excretion. On pig farms, for example, 40–95% of the nitrogen excreted may be lost before the manure is applied to the field. Much of that, perhaps 10–40% of the N lost, may occur from the barn even before storage. Ammonia losses from cattle manure are often less than from pig manure, probably amounting to less than 50% of the total N content.

Losses of N during storage of manure can also be high, depending on method of storage. In a US study, about 60–80% of N was lost from pig manure in lagoons exposed to air, compared to losses of only 30–65% from that stored in underground pits and later spread as liquid. Another estimate suggests that the proportion of pig manure N lost as NH_3 is less than 10% for anaerobic storage, 10–25% for semi-aerobic systems, and 25–85% during composting. The differences reflect the degree of exposure to air and the amount of water and acid present.

Some NH_3 is also released when manure is applied to land, particularly if a slurry is sprayed into the air. Most loss occurs shortly after application. For example, a study of NH_3 loss from cattle manure showed that about half of the total emission occurred within 1 day (Fig. 33).

Figure 33

Pattern of NH_3 loss from manure applied to the surface of soil. (S. McGinn, AAFC)

Another potential source of NH_3 is fertilizer. Two forms, both widely used in Canada, are especially important: anhydrous ammonia (pure NH_3) and urea. When anhydrous ammonia is injected into soil, it normally converts immediately to NH_4^+ in soil water and then is held tightly by the soil. If the soil is extremely dry, however, as much as 20% of the NH_3 can escape. On the other hand, if it is so wet that the soil does not close up after injection, as much as 50% can be lost. Urea fertilizer, like the urea in livestock manure, quickly converts to NH_3 and CO_2 after it is applied. If the fertilizer is not mixed into the soil, large amounts of NH_3 can be released to the atmosphere.

A third possible source of NH_3 from farms is crop residues. Appreciable amounts of NH_4^+ can be produced during the decay of N-rich residues like legume green manures. If the residues are allowed to decay on the soil surface, some of this NH_4^+ may convert to NH_3 and be lost to the atmosphere.

Based on data from 1990, NH_3 emissions from all sources in Canada amount to about 520 Gg (thousand tonnes) of N per year. Of this, about 90% comes from agriculture, largely from livestock production (Table 17). These estimates, however, are still preliminary.

Table 17 Estimated ammonia emissions from Canadian agriculture in 1990

Source	NH_3 emission (Gg N)
Animals	
Dairy cattle	incl. with beef
Beef cattle	211
Pigs	76
Poultry	88
Sheep/lambs	2
Horses	4
Total animals	381
Fertilizers	
Urea	71
Ammonium sulfate	2
Ammonium nitrate	2
Anhydrous ammonia	4
Nitrogen solutions	2
Ammonium phosphates	6
Total fertilizers	87
Total agriculture	468

Reducing ammonia emissions

Producers can reduce the emission of NH_3 from farms in a number of ways. In general, these methods rely on absorbing NH_3 in water or acid, preventing excessive N excretion by livestock, and minimizing exposure of NH_3 sources to the air. Specific examples of control methods include the following:

Use improved methods of fertilizer application: Farmers can reduce ammonia loss from fertilizer by ensuring good contact between the applied fertilizer and moist soil. They should place urea either below the soil surface or till it into the soil immediately after applying it to the surface. Injecting anhydrous ammonia into moist soil at sufficient depth prevents it from diffusing to the surface.

Minimize nitrogen excretion from livestock: The most basic way of reducing NH_3 emission from animal wastes is to produce less manure N in the first place. Although animals cannot avoid excreting N, farmers can reduce the N content of the manure by using rations with a better N balance, by avoiding excessive N in the diet, or, possibly, by adding bacteria that help convert uric acid (a forerunner of urea) to nitrate. Use of these practices could reduce N excretion by up to 25% in cattle, pig, and broiler poultry operations. Indeed, simulation models suggest that, for Quebec conditions, better diets could reduce the N content of pig manure by up to 60%. Nitrogen excretion can also be reduced, indirectly, by using breeds of livestock, feed formulations, or other practices that improve animal

performance and, hence, the product yield per unit of manure N.

Improve manure handling in the barn: Large amounts of NH_3 can be emitted in the barn when the manure is exposed to air. Farmers can minimize this exposure by removing manure frequently; washing barns with water, which absorbs NH_3; collecting liquid wastes in deep, narrow channels, to reduce surface exposure; and, in poultry barns, maintaining a deep layer of litter. As well, maintaining cool temperatures can reduce emission of gaseous NH_3. In Europe, changes in handling procedures (including diet) have reduced NH_3 release from pig barns by 45%.

Improve manure storage: Farmers can reduce ammonia loss during manure storage by minimizing exposure to air and lowering temperature. For example, applying a cover of mineral oil, straw, or peat over lagoons or tanks holding pig manure can reduce losses. Covers placed on tanks can cut NH_3 losses by two-thirds, and a thin layer of mineral oil on a slurry can reduce emissions by more than 30%. As well, adding acids to manure or covering composting manures with mildly acidic peat can minimize NH_3 loss. Ammonia is readily absorbed and held by acid, preventing escape to the atmosphere. Farmers can achieve reductions of at least 75% by using peat moss, sulfuric acid, or phosphoric acid during storage.

Use more effective application procedures: Ensuring quick and effective mixing with soil can minimize losses of NH_3 during application. For example, tillage or irrigation immediately after application drastically cuts emissions (Fig. 34). Farmers can also reduce

losses by applying manure before rain, injecting slurry directly into soil, or using diluted slurry for irrigation. Where they must apply slurry to grassland, banding it on the surface, rather than spraying it, can reduce losses. Finally, since rate of gaseous loss is related to temperature, applying NH_3 in cool weather (though not on frozen soil) can curtail emission.
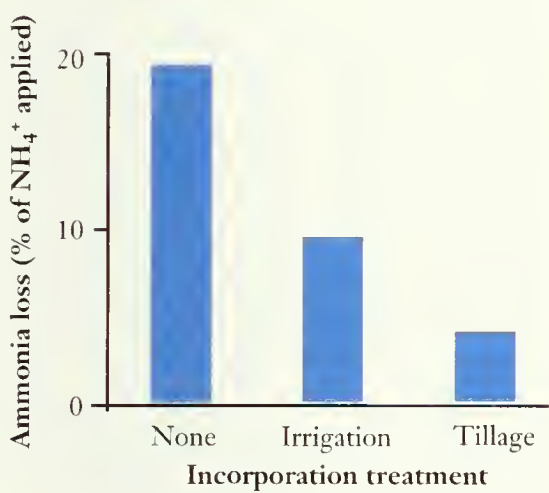

Figure 34
Proportion of manure NH_4^+ volatized within 8 days of application as affected by irrigation or tillage. (S. McGinn, AAFC)

This list shows several ways of cutting NH_3 emissions from agriculture. Not all these are practical or even advisable in all cases. For example, incorporating manure by ploughing is not compatible with the no-till systems advocated elsewhere. Nevertheless, given the number of options available, large cuts in emissions are probably easier for NH_3 than for some of the other gases, notably N_2O. With increasing attention to health, environmental, and odor issues related to NH_3, efforts to achieve such reductions will likely increase in the future.

Composting

Gases emitted during composting of organic waste may include CO_2, NH_3, CH_4, N_2O, and NO. Smaller quantities of reduced sulfur and nitrogen compounds may also be produced in anaerobic microsites. The form and quantity of gaseous compounds emitted during composting depends on the material being composted and the method used. Odor-producing compounds can be virtually eliminated with a properly designed aeration system. A biofilter system in enclosed composting facilities also ensures odor-free exhaust air.

Methane emission can also be eliminated with adequate aeration. Ammonia emission is controlled by the available C:N ratio of the composting material and by the aeration system used. When NH_3 emission occurs, it is usually early during the composting process. Ammonia may be captured using a scrubber. The factors influencing N_2O and NO emissions during composting are not well understood. Researchers are working toward a better understanding of N_2O emissions during composting and strategies to minimize emissions. A well-designed compost facility should not negatively affect the health of our air.

(J. Paul, AAFC)

The Netherlands has decided that, by 2000, NH_3 emissions must be no more than half of those in 1980. There, the annual N deposition has reached 85 kg/ha in parts of the country. Though deposition rates in Canada are usually much lower, high rates of deposition may already occur in local areas of intensive livestock production.

Other odors

Ammonia is only one of the gases released from farms that has an unpleasant odor. Many other gases also irritate the human nose. Some of these are not only unpleasant but also dangerous. Perhaps the most noteworthy is hydrogen sulfide (H_2S), a poisonous gas with the smell of rotten egg. High concentrations of this gas can be released when liquid pig manure in tanks is stirred. It can be fatal to humans, though only at high concentrations produced where ventilation is poor. Many other compounds, although not known to be poisonous, have an objectionable odor; more than 150 such compounds have been identified in pig manure alone.

To date, people have perceived farm odors only as nuisances, but awareness of this problem is now growing. Indeed, some countries have already established regulations regarding allowable odor intensities.

Odor-causing gases can come from many sources. Some of the most offensive arise from organic substances decaying in the absence of oxygen. The decomposing matter may be manure, effluent from manure piles, silage, plant debris, or a wide range of other organic materials. When decomposed without an adequate oxygen supply, they are not completely broken down into CO_2 and simple salts but rather are released as various intermediates such as organic acids, alcohols, aldehydes, sulfides, and CH_4. Of these, the compounds with the most offensive odors are the volatile organic acids.

Many odor-causing compounds come from the same source and therefore occur together. For example, volatile organic acids are often found with NH_3 and H_2S. Given the many compounds involved, odors are not easily measured and quantified. Indeed, the most sensitive and reliable sensor is still the human nose. One way to measure odor intensity is to count the number of times an air sample has to be diluted with fresh air before its odor becomes nearly imperceptible. A panel of human evaluators is used to determine the number of "dilutions to the threshold" (DT), which may range from 0 to 200 or more. On this scale, a reading of 170 DT or higher would be considered "unacceptable." The lowest value achievable within a feedlot operation is about 7 DT.

A variation on this approach is to compare the air sample with known concentrations of a reference compound, like butanol. With this method, the intensity of odor is reported in terms of equivalent concentrations of butanol. The scale normally ranges from 0 to 80 ppmv butanol (the highest intensity to which the nose is responsive). Most ambient odors have a rating of less than 60 ppmv butanol.

Researchers have used these techniques to evaluate the odor from various types of farms. Odors from pig farms usually rate "high" to "very high," whereas poultry and cattle operations normally rate "high," comparable to that of paper mills, petrochemical plants, and oil refineries. Of course, odor intensity varies considerably depending on wind speed, air stability, humidity, and distance from source.

Producers can reduce the intensity of odors from farms in several ways. The most obvious, perhaps, is to plan the farm layout carefully, placing sources of odor, like barns and lagoons, downwind and far from dwellings. Other methods include cleaning and washing barns frequently, aerating stored manure (although this action may favor NH_3 release), injecting slurries, and immediately incorporating solid manures after they are applied. Finally, various chemicals and bacterial cultures have been proposed for odor control, but their cost is often high and their efficacy limited. One possible approach is to add calcium bentonite, a clay with high absorption capacity, to animal diets. This additive has even been found to enhance weight gain under some conditions.

Nitrogen oxides

Nitrogen oxides, upon reaction with volatile organic carbon (VOC) in the presence of sunlight, produces O_3, the main constituent of smog. Nitrogen oxides come mostly from combustion of fossil fuel, and are usually linked to automobiles and industrial sources. But farm machinery also uses a lot of fuel; for example, agriculture accounts for about 25% of the heavy-duty diesel vehicles in Canada. Although the importance of farm machinery as a source of nitrogen oxides is not known, its contribution to smog is likely negligible. Even so, energy-conserving steps like reduced tillage can reduce somewhat the emissions of nitrogen oxides.

Nitric oxide (NO), like N_2O, is sometimes produced in soil as a by-product of nitrification and denitrification. In rural areas, the release of NO from this source can rival that of nitrogen oxides from industrial sources. Using methods similar to those described for N_2O can probably reduce the emission of NO from agricultural soils.

Aerosols

Aerosols are solid particles in atmosphere, either formed in the air by reactions among gases or injected into the air by processes on the ground. They consist of a variety of materials and vary in size from less than 1 micrometre (μm, one-thousandth of a millimetre) to the size of a sand grain. The main sources of aerosols are natural events like volcanoes, sea spray, forest fires, and soil erosion. But some aerosols are also produced by human activity, like combustion of fossil fuel.

Particles smaller than 2.5 μm are a serious concern for both visibility and human health. Aerosols absorb and reflect light, producing the haze in cities. They can also be breathed in and stay in the respiratory system causing respiratory illness and even cancer.

Aerosols also have an important effect on global climate. They provide the nuclei or "seeds" that encourage cloud to form. They also reflect solar radiation, thereby cooling the earth. In some regions, the cooling effect of aerosols is now about the same as the warming effect of CO_2, though it is not expected to increase enough to offset further increases in CO_2.

The amount of aerosols produced by Canadian agriculture has not been measured routinely but is probably

small. Nevertheless, farms do emit some aerosols of two types: primary particles, which are released intact into the air (e.g., field dust, soot, and pesticide crystals); and secondary particles, which are formed in the air from gases emitted by agriculture (e.g., NH_4^+ particles from NH_3). Some secondary particles were described earlier; here we focus only on primary particles.

The most common aerosol from Canadian farms is probably dust from soil erosion. When soil is dry, loose, and without plant cover, the wind can pick up surface particles and carry them great distances. The problem was most severe in the southern prairies during the dirty thirties, when as much as several centimetres were lost from some fields, obscuring the sky and depositing dust everywhere. Although conservation measures now prevent such large-scale dust storms, occasional erosion episodes still occur locally.
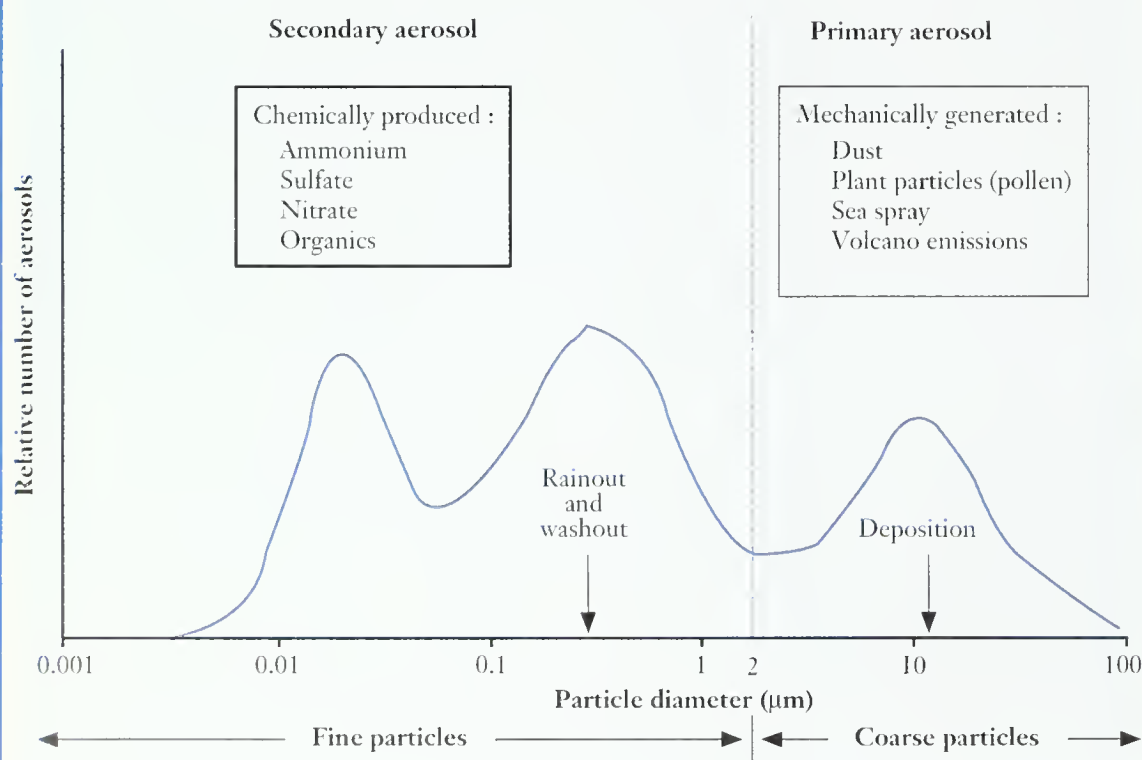
Erosion occurs in two steps. The wind first detaches tiny soil grains (0.1–0.5 mm), which then act as abrasives on larger soil particles. The detached particles travel in three ways: saltation, creep, and suspension. In saltation, particles bounce across the surface; in soil creep, larger particles (0.5–1.0 mm) roll and slide after they are hit and accelerated by "bouncing" particles. These two processes account for most erosion. But in fine-textured soils, with many particles smaller than 0.1 mm, soil may be lifted high above the surface (suspended), creating dust clouds that can travel for hundreds of kilometres. Eventually, the suspended particles settle out in calm winds or are washed out in rain.

After the bad experience of the 1930s, researchers developed many erosion control measures. Some of these are now commonly used: reduced tillage, keeping residues on soil surface, shelterbelts, and less-frequent use of summer fallow. Consequently, although about half of Canada's agricultural soil is moderately or highly susceptible to wind erosion when it is bare, less than 5% of cultivated land is now at high risk.

Although severe and widespread erosion has been largely halted, some dust from farmland still enters the air through localized erosion events or during tillage and other farm

Aerosol size distribution and global warming

The size distribution of an aerosol is closely related to its source. Coarse particles are generated mainly from mechanical processes, such as wind, whereas fine particles are produced by chemical reactions. Size distribution and chemical contents of aerosols are important factors determining global climate change and visibility. Aerosols have a cooling effect, which offsets, in part, the warming effect of greenhouse gases.

Secondary aerosol

Chemically produced :
Ammonium
Sulfate
Nitrate
Organics

Primary aerosol

Mechanically generated :
Dust
Plant particles (pollen)
Sea spray
Volcano emissions

Relative number of aerosols

Rainout and washout

Deposition

Particle diameter (μm)

Fine particles   Coarse particles

(T. Zhu, Ottawa, Ont.)

operations. The dust emitted from soils is not just inert mineral particles. It may also contain seeds, pollen, and plant tissue, as well as agrochemicals, including pesticides. These materials can cause health problems and, in the cases of pesticides, contaminate other environments.

Another agricultural aerosol is smoke from burning of weeds or straw. Smoke contains soot (particles of carbon) that can cause respiratory problems. Until recently, burning excess straw was commonly practiced in areas with high yields, like southern Manitoba. Now provincial and municipal regulations have almost eliminated this practice. Some excess straw now goes to industrial uses, like "strawboard," which eliminates the health hazard and also provides additional income.

Ultraviolet radiation

Background

The sun produces radiation with a wide range of wavelengths. Some wavelengths stimulate receptors in human eyes, so that we can "see" them. Thus, radiation with a wavelength of about 390 nm (10^{-9} m) to 760 nm is called "visible light." Within this range, different wavelengths correspond to various colors: the shortest wavelengths correspond to violet, the longest to red. But the sun also produces radiation outside the visible range. Radiation of wavelength longer than red is called infrared radiation; radiation of wavelength shorter than violet is called ultraviolet radiation.

Soil erosion in southern Alberta, 1935

The energy of radiation increases as the wavelength gets shorter. Ultraviolet radiation, therefore, has much higher energy than visible light, enough to cause severe injury to living things. But little of the sun's UV radiation reaches the earth's surface; most is filtered out by O_3 in the upper atmosphere (the stratosphere). This effective screening of UV radiation occurs despite the very low concentration of O_3. If all the O_3 were placed in a layer at the earth's surface, it would be only 3 mm thick. Because it protects the earth's surface from damaging UV radiation, O_3 in the upper atmosphere (unlike that at ground level) is essential to life.

Because of its vital function, scientists were alarmed to learn, in recent decades, that the amount of O_3 in the upper atmosphere is declining; that is, the O_3 layer is "thinning." Worldwide, O_3 concentrations have already

declined by an average of 3%. But much of the depletion has occurred near the poles. Average values in Canada have declined by about 6% since 1980. Decreases near Antarctica have been as high as 60%, forming the so-called "Antarctic ozone hole."

The thinning of the O_3 layer, scientists now believe, is caused by the release of various gases from industrial activity. Most noteworthy of these are the chlorofluorocarbons (CFCs) that are used in refrigeration and as a propellant in aerosol cans. These molecules, which have a very long life, migrate into the upper atmosphere where they cause O_3 to break down into O_2. Another gas known to break down O_3 is methyl bromide, used throughout the world as a fumigant to kill insects and nematodes in farm fields, greenhouses, and food storage and processing plants. Methyl bromide

accounts for up to 10% of global O_3 losses. Finally, nitric oxide (NO) can accelerate O_3 breakdown. This gas is produced naturally in the atmosphere from N_2O. Increases in N_2O emissions, therefore, can also indirectly cause O_3 breakdown.

Once they had recognized the cause of O_3 depletion, the international community set up an agreement (Montreal Protocol on Substances that Deplete the Ozone Layer) to curb emissions of gases like CFCs and methyl bromide. All developed countries have agreed to eliminate the use of CFCs by 2000 and the use of methyl bromide by 2015. Canada has committed to eliminate use of methyl bromide by 2001 (with some exceptions where no practical alternatives are available). Already in 1995, the use of methyl bromide had declined by about 40% relative to that in 1990. Promising alternatives to methyl bromide include using other chemicals, diatomaceous earth (which physically damages insects), and integrated pest management strategies.

By adopting strict controls on CFCs and other O_3-depleting substances, we can probably halt the continued depletion of O_3 by about 2000. But, because of the long life of CFCs already in the atmosphere, it may take until 2060 before O_3 concentration returns to its pre-1980 levels. Consequently, we can expect high UV intensity for several more decades and need to consider some of its effects on agricultural production.

Soybean leaves damage by UV-B radiation

(M. Morrison, AAFC)

Effect of ultraviolet radiation on crops

Because some UV radiation reaches the earth's surface, terrestrial plants have evolved protective mechanisms. Some produce pigments, similar to sun screen, that absorb UV radiation. Others, like soybean, have UV-absorbing pigments in fine hairs on the upper surface of leaves (hence, symptoms of UV radiation are often more severe on the under surface of leaves). As well, most plants have some ability to repair cells and DNA damaged by excessive UV.

Despite these defense mechanisms, high exposure to UV can injure cell membranes and DNA within cells. Perhaps its most damaging effect is to disrupt the chloroplasts (the chlorophyll-containing organs where photosynthesis occurs). Damage to the chloroplasts reduces photosynthesis, which, in turn, can reduce plant growth.

Many recent studies have evaluated the effects of increased UV on plant growth using a combination of UV filters and UV lamps to produce a range of UV intensities. Much of the research has focused on UV-B, a band of wavelengths from 290 to 315 nm. Ultraviolet radiation with longer wavelengths (UV-A) has less energy and is therefore less damaging. Ultraviolet radiation with shorter wavelength (UV-C) is absorbed so effectively by the atmosphere that it never reaches the earth's surface.

Scientists have observed plant growth or yield effects from UV-B in numerous crops, including timothy, soybean, tomato, and canola. The effects of UV-B on yield are not always consistent, because some varieties yield more with increased UV-B than without. Studies with some species (e.g., corn) showed no damage even at high UV-B levels. Furthermore, as observed with canola and soybean, the response to UV-B seems to vary among varieties of the same crop. For example, in a study of eight soybean varieties, six had lower yield under high UV-B, but two had higher yields. Consequently, though there is good evidence of potential yield loss from increased UV-B intensity, there are many factors which complicate the results of UV-B studies.

To evaluate the potential effects of increased UV intensity on agriculture, researchers measured the growth response of 100 varieties from 12 crops to an increase in UV corresponding to a 20% reduction in O_3. Of these 100 varieties, 40 showed no effect. A simple model, based on these and other data, describes the sensitivity of crops to UV-B (Table 18). "Tolerant" crops would show little yield loss from an increase in

Table 18 Sensitivity of Canadian crops to UV-B radiation

Tolerant	Intermediate	Susceptible
Wheat	Barley	Oat
Sunflower	Rye	Pepper
Corn	Soybean	Cucumber
Tobacco	Pea	Mustard
Red clover	Tomato	Canola
Alfalfa	Potato	
Bluegrass	Soft fruit	
Orchardgrass		
Cabbage		

(M. Morrison, AAFC)

UV-B radiation as high as 20% increase over 1980 levels. Crops with "intermediate" sensitivity may have yields reduced by 1, 2.5, and 5% with increases in UV-B of 5, 10, and 20%, respectively; whereas "susceptible crops" may have yields reduced by 2, 5, and 10% with the same UV-B increments. Using these estimates, we can predict potential economic losses from increases in UV-B. For example, a 5% increase in UV would result in crop yield losses of about $90 million per year; a 20% increase in losses of about $400 million.

Ultraviolet radiation may also affect crop quality. Exposure may produce surface blemishes on vegetables and fruits or may affect flavor by causing increased pigment production. In one study, for example, amounts of UV-B-absorbing pigments in broccoli were higher with UV-B than without UV-B exposure. All these effects can reduce the value of the crop.

There may also be ecological effects of UV on plant communities. Under high UV-B, species with higher tolerance may out-compete susceptible species. This effect could be important in mixed grasslands or it could alter weed-crop competition. Furthermore, elevated UV-B can affect seed production, because exposed reproductive parts may be especially vulnerable.

Aside from effects on yield, quality, and ecology of crops, elevated UV-B could also have other implications. For example, it could affect animal health, plant diseases, pests, and pesticide efficacy. These effects have yet to be studied.

Research into ways of reducing the UV-B effect on crops has made little progress as yet. Given the differences in response among plant species and varieties, however, it may be possible to limit economic losses by selecting UV-B tolerant varieties.

Pesticides

Most farms in Canada use some pesticides to control weeds, insects, and diseases. Many of these pesticides have at least some toxicity for humans or potential adverse effects in the environment. Pesticides applied to the soil and crops can either drift while being applied or volatilize afterwards. Once in the air, wind can transport the pesticides long distances before depositing them on soil or water. Pesticides deposited in the Great Lakes, for example, have caused concern over water quality.

Some of the earlier concerns about pesticides are no longer as valid today because older, persistent pesticides (like DDT) are no longer used in Canada. Farmers now usually use newer formulations designed to control specific pests and to be easily degraded by soil microbes. Further, pesticides are now often applied at much lower rates, typically at grams per hectare rather than kilograms per hectare as in the past.

Despite the improvements in current pesticides, however, further precautions may be helpful to reduce losses to the atmosphere. For example, spraying only during calm conditions and ensuring that droplets are large enough to prevent their suspension in the air reduces pesticide drift. In some cases, it may be possible to reduce rates or frequency of pesticide application by relying on other methods of pest control. For example, biological methods can now control some weeds and insects. The use of "Integrated Pest Management" (IPM) techniques, which rely on optimum combinations of chemical, biological, and cultural methods, may provide the best approach to reducing pesticide usage.

Pesticides help to produce high yields on Canadian farms. Given their potential effects on human health and the environment, however, farmers need to be vigilant to prevent pesticides from leaving the target site.

Agrochemicals

Agrochemicals, such as insecticides and herbicides, can be released into the environment by drift, volatilization, and runoff. For example, some have found their way into the Great Lakes. Scientists use a high-volume sampler, installed in an aircraft, to measure agrochemicals fluxes on a regional scale.
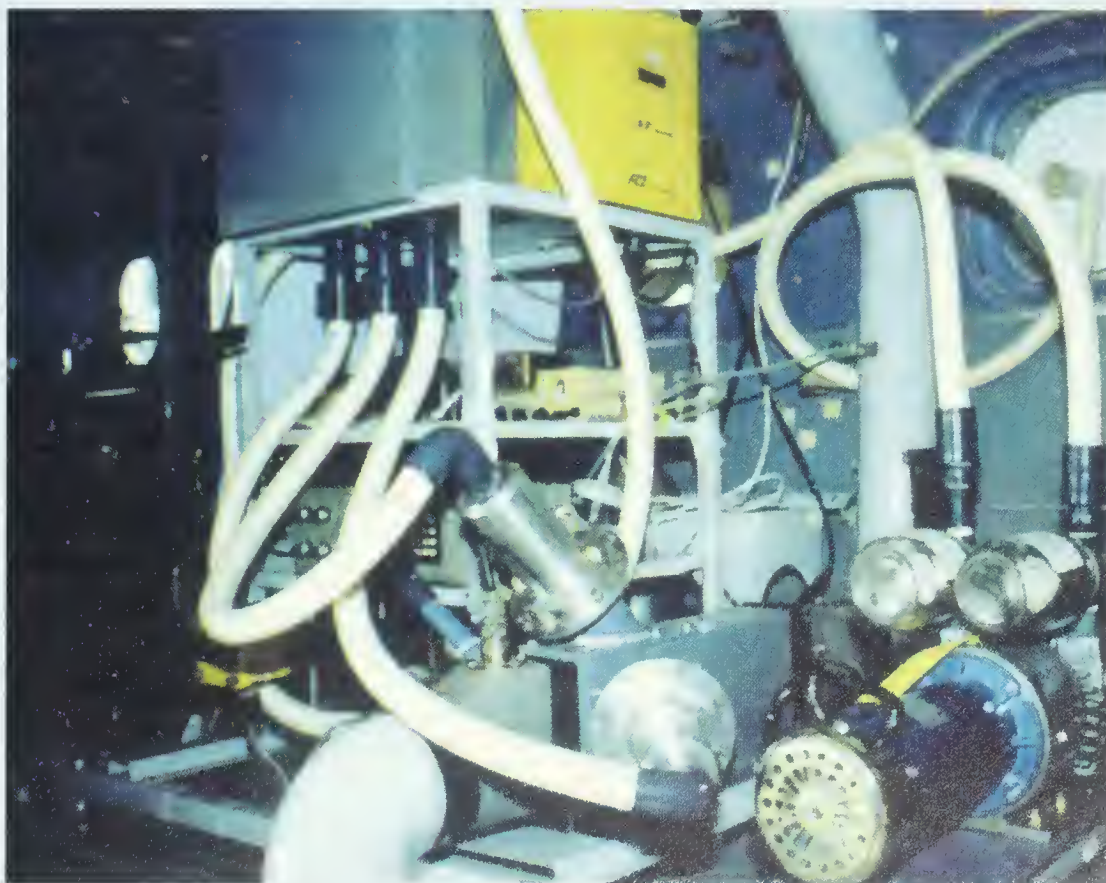
(G. St-Amour, AAFC)

5. Conclusions

The crops, livestock, and soils that make up our farms are immersed in air. They give out gases and particles that change the air's composition, both locally and far afield. At the same time, they take in and are affected by air that has been altered by industry and other human activity. As a result, farms are sensitive markers of the health of our air.

Current status

One of the main concerns in recent years has been the release of greenhouse gases into the atmosphere. We now know that farms account for about 10% of Canada's greenhouse gas emissions. About two-thirds of the emissions are in the form of N_2O and one-third CH_4. Livestock and manure account for about 58% of these emissions, cropping practices for 37%. At one time, agriculture was also an important source of CO_2, mostly from cultivated soils, but these emissions have abated to almost negligible levels. Some uncertainty remains in these emission estimates, particularly for N_2O, which is released in sporadic bursts, making precise estimates difficult.

Agriculture also releases other materials into the atmosphere. It is the main source of atmospheric NH_3 and may also release some nitric oxide, dust, and pesticides into the air, though amounts are usually small.

Although farms release some gases into the air, which affect its composition, they are also, in turn, influenced by emissions from other sectors of society. One example is the ground-level O_3 that causes crop damage in areas of high population density. This O_3 affects the yield and quality of produce on nearby farms, which, because of their proximity to population centres, often grow high-value crops. Another example is the potential effect of increased UV-B radiation, which arises when industrial chemicals such as CFCs deplete O_3 in the upper atmosphere. We do not yet know, precisely, the effects of the higher UV-B on crops and animal health, but some damage may occur, particularly if intensity of UV-B continues to increase, as expected.

Opportunities to reduce emissions

The net release of gases—N_2O, CO_2, CH_4, and NH_3—is usually a symptom of the inefficient use of resources. Release of excessive CH_4 from livestock means a waste of feed; loss of N_2O or NH_3 reflects inefficient use of N in fertilizers, crop residues, or manures; and excessive release of CO_2 reflects inefficient use of solar energy, stored as fossil fuel or plant C. Farmers can reduce emissions, therefore, by managing the farm N and C cycles more efficiently, to prevent gases from leaking into the environment. Because of improved efficiency, many practices that reduce emissions also have other favorable effects: reducing production costs, conserving soil and water, and improving ecosystem health.

Agriculture will always remain a source of some gases: CH_4, N_2O, and NH_3. Even the natural ecosystems replaced by farms release these gases. But,

improved efficiency of N and C use can minimize the amounts of emission. Reductions as high as 20–30% may be possible. Improved farming practices can actually result in net removal of CO$_2$ from the atmosphere, by storing C in soils. This increased storage could even help Canada meet its targets for reducing this greenhouse gas.

Future challenges

In much of this book, we have focused on current farm practices: how they affect our air and how, in turn, the changing atmosphere affects them. We have summarized estimates and processes that describe current agroecosystems. But we know that agricultural systems are always evolving; that many of the systems we have struggled to understand here may be obsolete just years from now. Thus, it is important to at least point to some impending changes and speculate about their possible effects.

One important factor is the continuing drive for higher agricultural productivity. As global population climbs, demand for farm products increases. Moreover, the economic survival of farms often depends on ever-higher output of products. The resulting gains in productivity may have some benefits; for example, they may help to build soil C by producing more crop residue. At the same time, however, the higher yield targets may require more fertilizers and other inputs that could release more greenhouse gas.

Economic factors are another consideration. As cost of inputs and price of products change, farmers alter their farming systems to maintain profits. Consequently, the area of land devoted to certain crops changes from year to year, which affects the release of greenhouse gases and other emissions. Perhaps the most dramatic

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Efficiency improvements

Market competition makes for more cost-effective production. Energy shortages and costs make producers more energy conscious. Similarly, faced with the possibility of global climate change, producers may be able to further increase their efficiency in using resources, thereby increasing the amount of food produced per unit of greenhouse gas emitted.

Examples of increased productivity in Ontario

Crops	1975	1991
Diesel fuel-equivalent of		
soybean produced (L/t)	174	95
corn produced (t/ha)	3.4	6.9

Dairy	1951	1991
Animals (million)	1.7	0.9
Milk (billion L)	2.4	2.5
Land area need to produce feed (million ha)	1.1	0.5
Manure generated (million t)	21.4	12.5

Eggs	1951	1991
Eggs produced (million dozen)	107	179
Land area need to produce feed (thousand ha)	129	61
Manure generated (kg/dozen eggs)	7.1	3.4

| Chicken	1951	1991
Meat produced (million kg)	45	299
Land area need to produce feed (thousand ha)	96	117
Manure generated (kg/kg meat)	12.6	3.9

These tables show that productivity has increased considerably in the selected periods. Energy per kilogram of soybean has halved in 15 years; and manure per unit of milk, eggs, or chicken has halved in 40 years. It may therefore be expected that fossil CO$_2$ and manure N$_2$O emissions per unit of production have also decreased.

example is the recent shift toward livestock-based systems. This change has far-reaching implications. On the one hand, higher livestock numbers usually mean more land in forages, which reduce atmospheric CO_2 by storing more C in soil. At the same time, however, increased livestock numbers can lead to more release of CH_4, N_2O, and NH_3. If the trend toward higher numbers of farm animals continues, then many of our current emission estimates will need to be revised and new measures of reducing emissions may be needed.

But it is not only the farming systems that will change. Environmental conditions that affect farms will themselves change over the next decades. Many scientists believe that climate will be noticeably altered by the greenhouse effect over the next decades; even small changes in temperature or precipitation would affect Canadian farms. Another important environmental characteristic has already changed measurably: the CO_2 concentration, already about 30% higher than in pre-industrial times, will likely double within the next century. Since CO_2 is the raw material for photosynthesis, this increase may have important effects on crop yield. Some even predict an increase in yields through "CO_2 fertilization." Other environmental conditions may change as well, including concentration of ground-level O_3 in populated areas, and the intensity of UV-B radiation. These changes, some of which are not easily predictable, may affect the way we farm in the next century. As well, they will alter the emissions from farms, thereby continuing the cycle between farms and the atmosphere.

Carbon dioxide "fertilization effect"

Higher CO_2 concentration can enhance crop yield by increasing photosynthesis and allowing more efficient use of water. This CO_2 "fertilization" is more pronounced in C_3 plants (e.g., wheat, soybeans, and most grasses) than in C_4 (e.g., corn and some grasses). Some scientists think that CO_2 fertilization can largely offset yield losses arising from climate change. Others suggest that the benefits may be overstated, because they overlook the interaction between increased CO_2 and other environmental conditions. More research on these questions is needed.
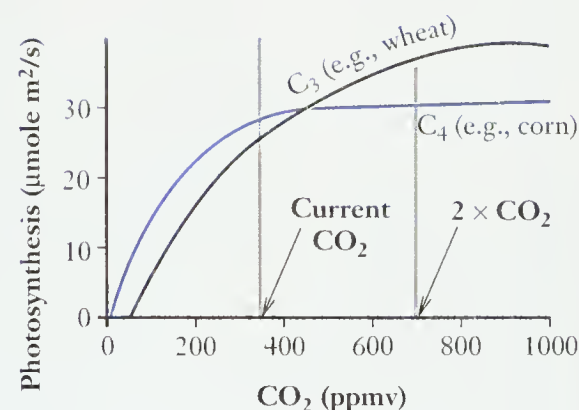
Organic farming—an alternative approach

Organic farming minimizes the need for off-farm inputs. It employs systems that avoid or largely exclude the use of synthetic fertilizers, pesticides, growth regulators, and livestock feed additives. Many believe that greenhouse gas emissions may be less for organic systems than for conventional agricultural systems.

Organic farms attempt to harmonize with natural systems. They rely on renewable resources and less input from fossil energy. The holistic view of organic farmers follows a natural systems approach to agriculture. Individual growers take daily decisions to make a living from the land, based on both economic and ecological considerations. With time, agroecosystems reach a steady state, where living and nonliving processes are in balance. For many, it is a way of life as much as a way of making a living.

The holistic systems approach requires an intimate knowledge of the interrelationships between soil, water, climate, and biology of the agricultural system. In addition, these systems also consider off-farm effects such as rural economics and sociology.

Generally, families on organic farms have traditions of environmentalism and are careful consumers of all resources. The day-to-day on-farm decisions of organic farmers are complex and require an in-depth knowledge of many areas of science. Organic farmers believe that their philosophy provides a gentler approach to the earth.

Both conventional and organic systems of agriculture aim to provide society with high-quality food, but some feel that organic farming also attempts to improve quality of the on-farm natural resources and to reduce potential environmental damage.

(J. Dormaar, AAFC)

Remaining questions

The unpredictability of future changes in farm ecosystems, along with uncertainties about even our current estimates of emissions, leave room for further study of the ties between our farms and the atmosphere. The most urgent goals may be the following:

- To improve further our estimates of current gas release, especially for N_2O. We need better ways of taking data from local measuring points and extending them to larger areas, up to the national level.

- To find ways that will help Canada meet its international commitments for reduced emissions of potentially harmful gases.

- To understand better how C, N, and other elements move through and among plants, animals, soil, water, and air. Such understanding will show us how the various gases and environmental issues are linked together and how they interact. As well, it will help us to predict better how changing farm practices will affect the environment.

- To learn how changes in our atmosphere will affect Canadian farming in the future. Of particular importance may be the effects of climate change (temperature and precipitation), increased CO_2 concentration, enhanced UV-B intensity, and increased ground-level O_3. We need to know how these will affect yields, crop types, animal productivity, pests, and production costs. As well, we need to understand how these changes will alter future emissions from agriculture to the air.

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Acknowledgments

The material presented in *The Health of Our Air* is derived from the work of many scientists who made valuable contributions to the Agriculture and Agri-Food Canada research initiatives on greenhouse gases and ground-level ozone. These included the principal investigators or team leaders, listed here as contributors, along with collaborators, colleagues, postdoctoral fellows, technicians, and graduate students. Grateful acknowledgment is made to all.

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A listing of the principal investigators and their project titles are presented in Appendix I for those who wish more detailed information.

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Acknowledgments are also due to the following individuals for their review of this manuscript and their helpful comments: T. Daynard, Ontario Corn Producers; S. Forsyth, National Agriculture Environment Committee; P. Strankman, Canadian Cattlemen's Association; K. Whittenberg and D. Burton, University of Manitoba; V. Runeckles, University of British Columbia; J. Farrell, Fertilizer Institute of Canada; E. Beauchamp, University of Guelph; G. Hamblin, Canadian Organic Advisory Board; and E. Gregorich and K. Beauchemin, Agriculture and Agri-Food Canada.

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The editors wish to thank the following for their valuable technical assistance in preparing the manuscript and figures for publication: S. Rudnitski, J. Sylvestre-Drouin, R. Riznek, and C. Merrill of Agriculture and Agri-Food Canada, and J.T. Buckley (Gilpen Editing Service).

Program Management

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